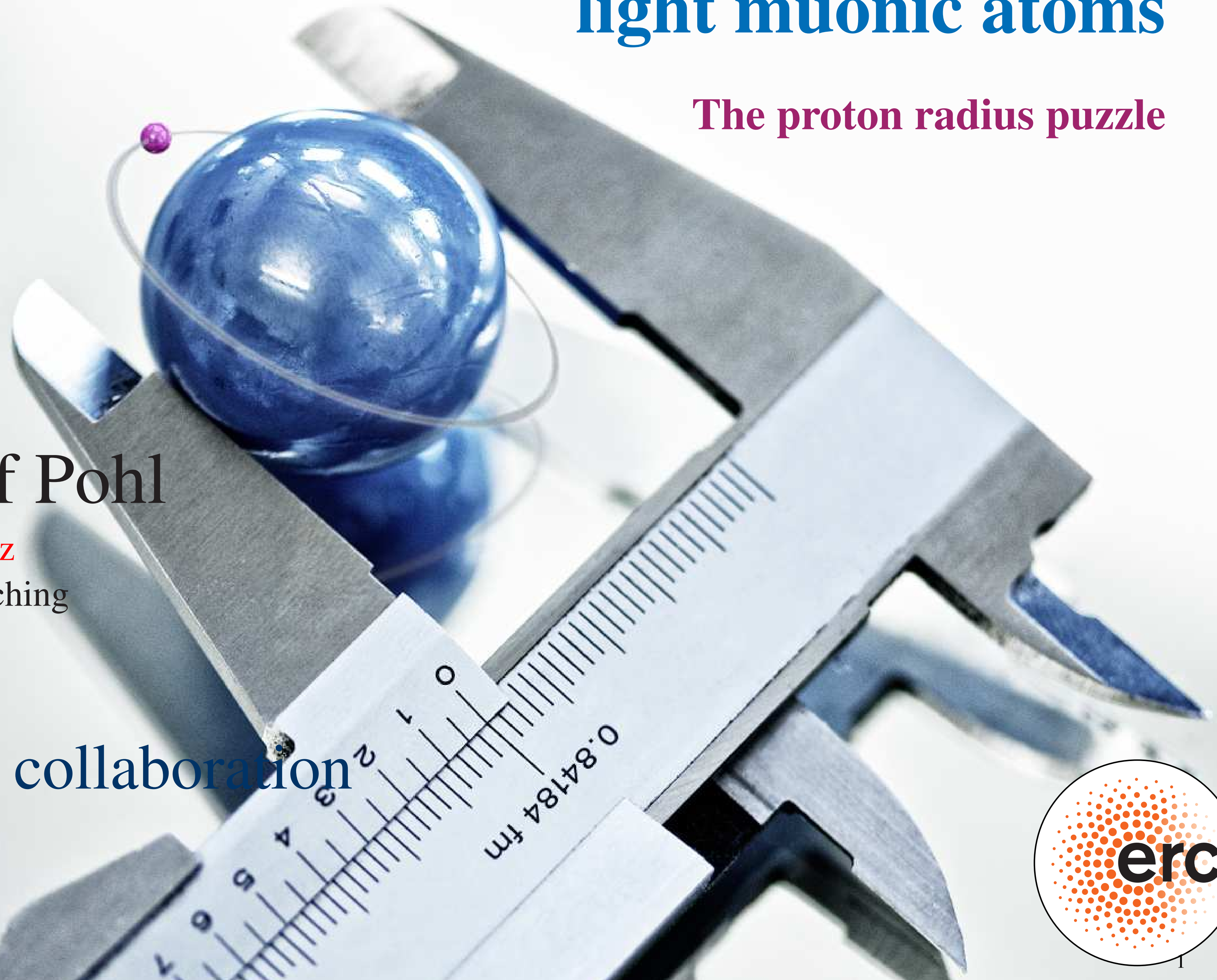
Laser spectroscopy of light muonic atoms

The proton radius puzzle



Randolf Pohl

JGU, Mainz

MPQ, Garching

for the

CREMA collaboration

Collaborators

CREMA (Charge Radius Experiment with Muonic Atoms) at PSI

A. Antognini, K. Kirch, F. Kottmann, B. Naar, K. Schuhmann, D. Taqqu	ETH Zürich, Switzerland
M. Diepold, B. Franke, J. Götzfried, T.W. Hänsch, J. Krauth, F. Mulhauser, T. Nebel, R. Pohl	MPQ, Garching, Germany
M. Hildebrandt, A. Knecht, A. Dax	PSI, Switzerland
F. Biraben, P. Indelicato, E.-O. Le Bigot, S. Galtier, L. Julien, F. Nez, C. Szabo-Foster	Labor. Kastler Brossel, Paris, France
F.D. Amaro, J.M.R. Cardoso, L.M.P. Fernandes, A.L. Gouvea, J.A.M. Lopez, C.M.B. Monteiro, J.M.F. dos Santos	Uni Coimbra, Portugal
D.S. Covita, J.F.C.A. Veloso	Uni Aveiro, Portugal
M. Abdou Ahmed, T. Graf, A. Voss, B. Weichelt	IFSW, Uni Stuttgart, Germany
T.-L. Chen, C.-Y. Kao, Y.-W. Liu	Nat. Tsing Hua Uni, Hsinchu, Taiwan
P. Amaro, J.P. Santos	Uni Lisbon, Portugal
L. Ludhova, P.E. Knowles, L.A. Schaller	Uni Fribourg, Switzerland
A. Giesen	Dausinger & Giesen GmbH, Stuttgart, Germany
P. Rabinowitz	Uni Princeton, USA

Hydrogen group at MPQ

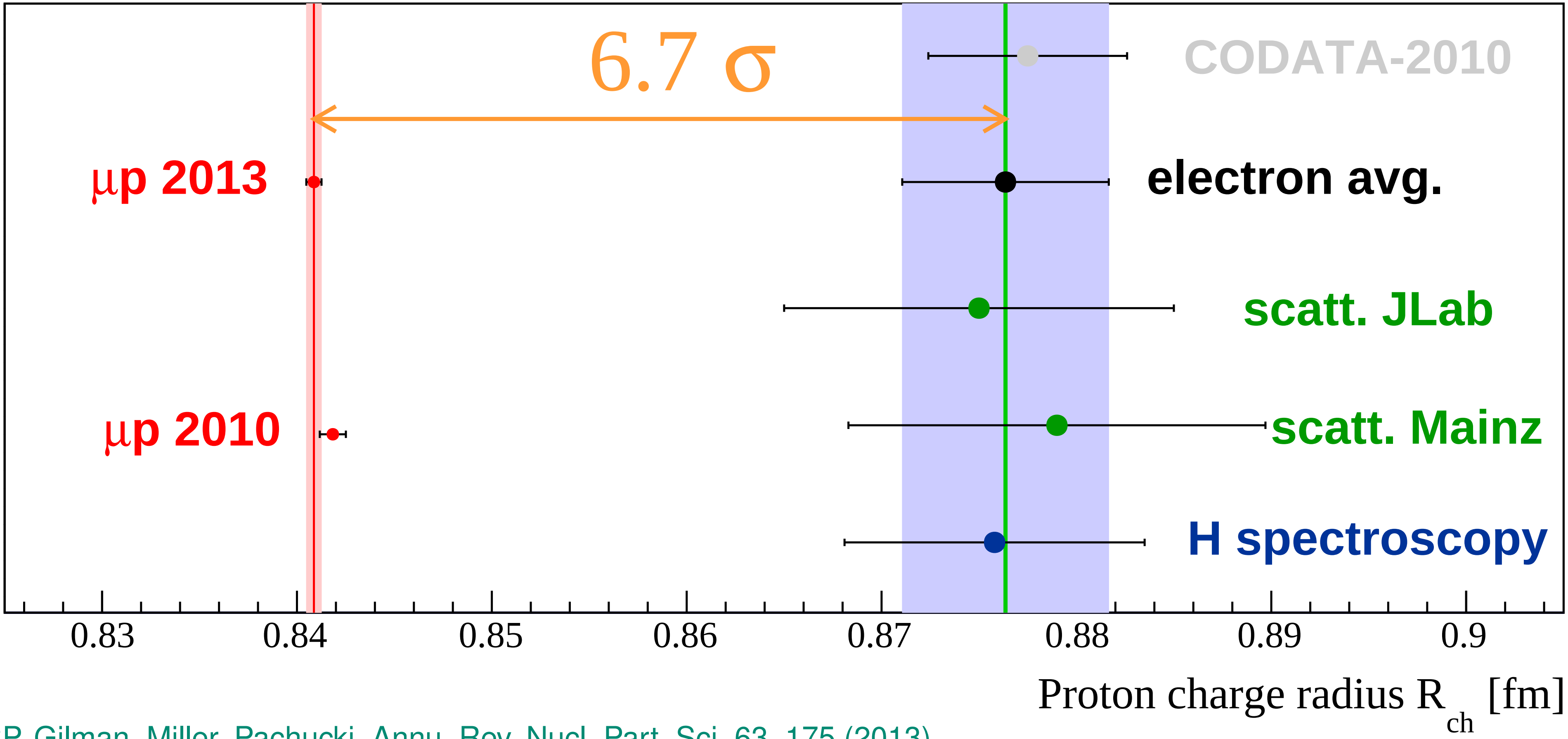
A. Beyer, L. Maisenbacher, A. Matveev, C.G. Parthey, J. Alnis, R. Pohl, Th. Udem, T.W. Hänsch	MPQ, Garching, Germany
K. Khabarova, N. Kolachevksy	Lebedev Inst., Moscow, Russia

The proton radius puzzle

The proton rms charge radius measured with

electrons: 0.8770 ± 0.0045 fm

muons: 0.8409 ± 0.0004 fm



RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

The proton radius puzzle

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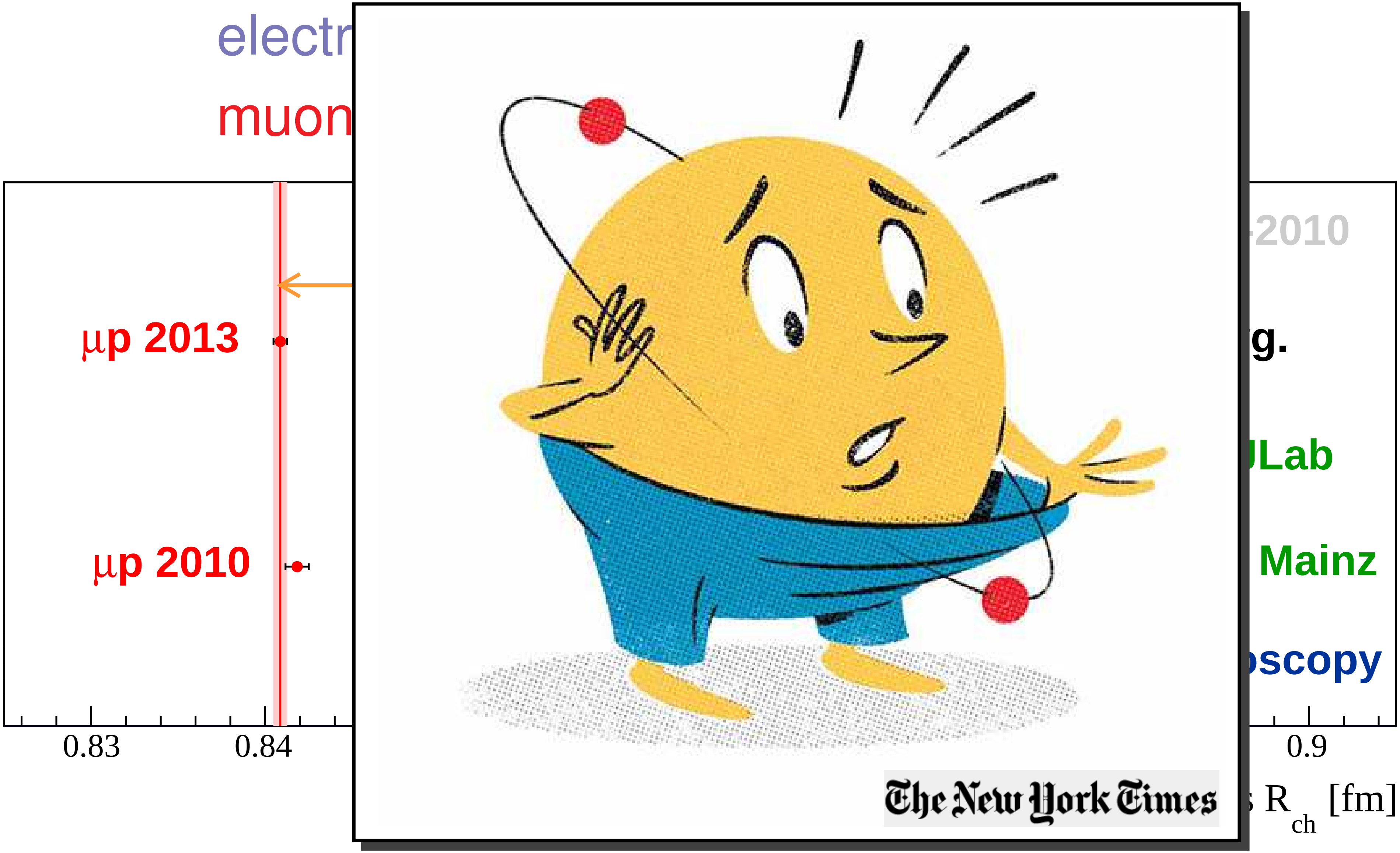
electr

muon



A proton radius puzzle?

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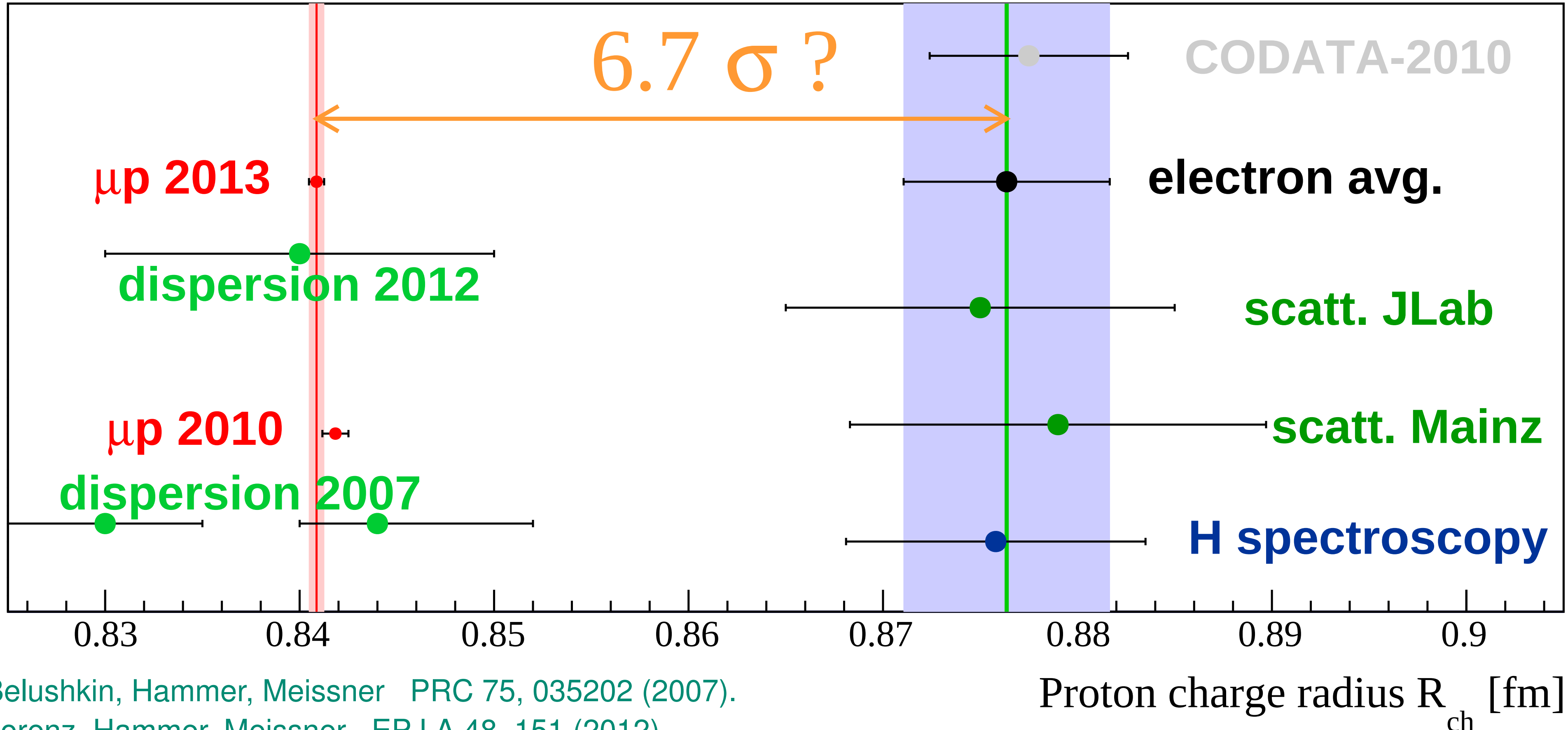


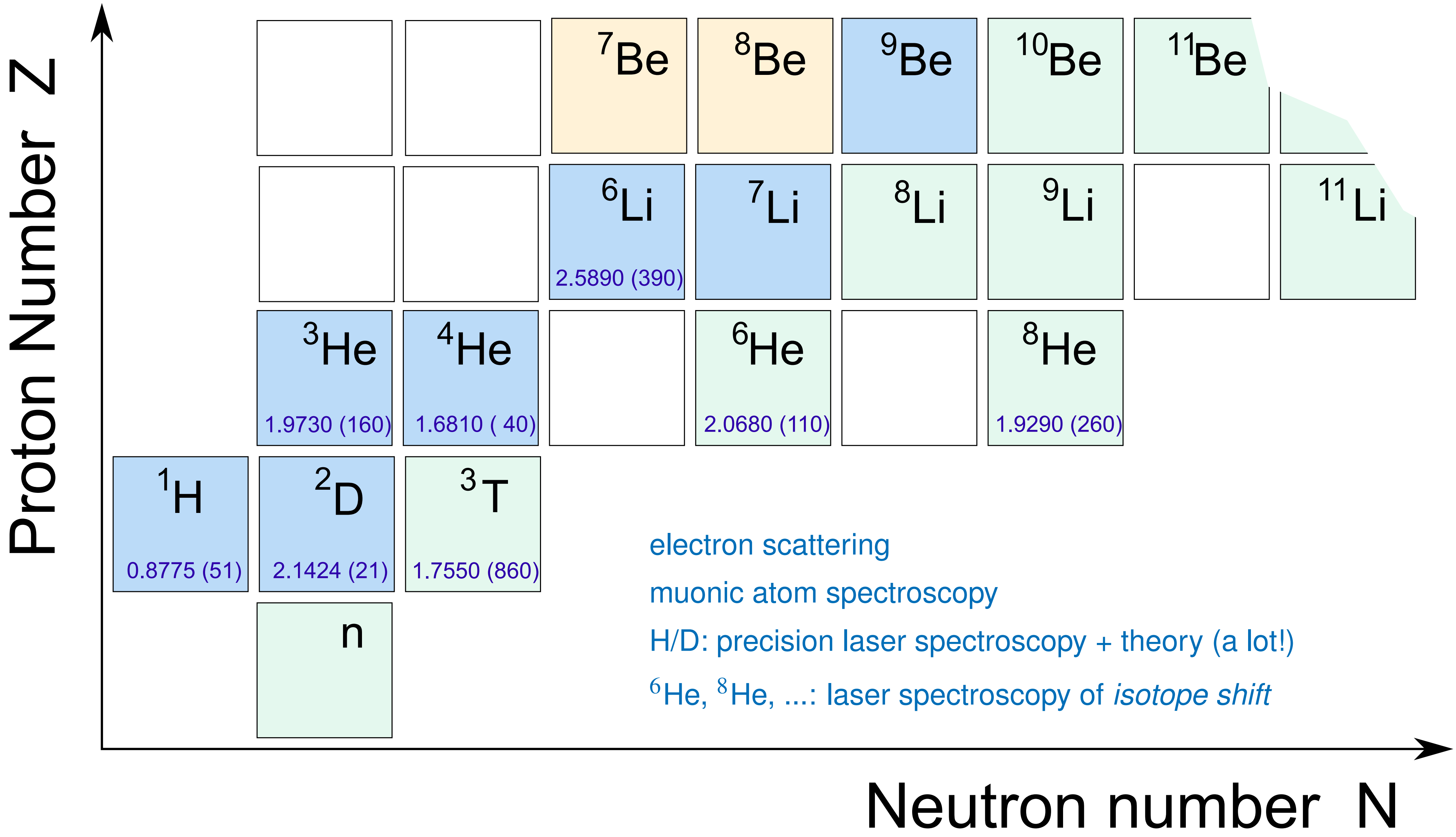
Belushkin, Hammer, Meissner PRC 75, 035202 (2007).

Lorenz, Hammer, Meissner EPJ A 48, 151 (2012).

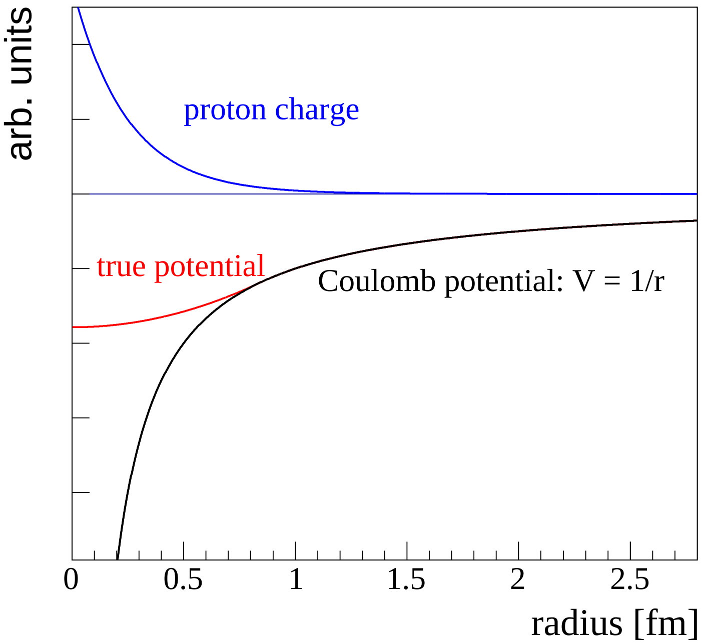
Outline

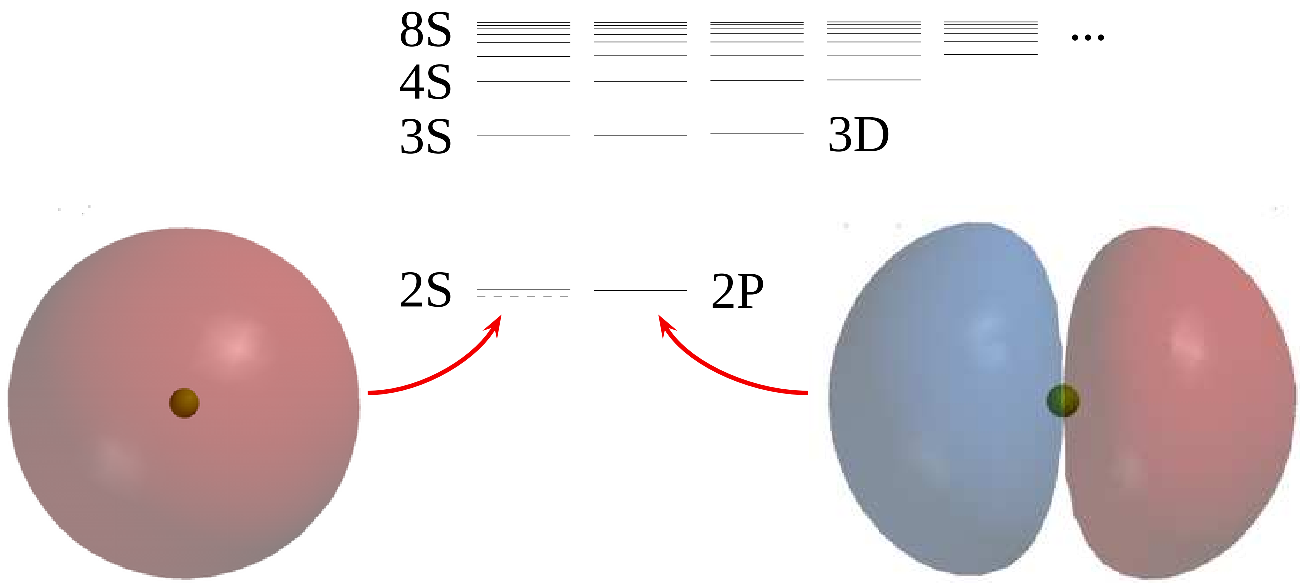
- Introduction:
  How large are the proton, deuteron, helion, alpha...?
  Atomic vs. nuclear physics
- Muonic hydrogen:
  Size does matter!
- Laser spectroscopy of muonic atoms/ions
- New measurements:
  - Muonic deuterium $\rightarrow$ Another puzzle!
  - Muonic helium
  - Regular hydrogen $\rightarrow$ New Rydberg constant!
- Future:
  - HFS in muonic hydrogen and helium-3
  - X-ray spectroscopy of radium etc.
  - Lamb shift in muonic Li, Be, ...
  - 1S-2S in regular tritium (triton radius)
  - ...

Charge radii of light nuclei



Atomic physics





S states: max. at r=0

Electron sometimes inside the proton.

S states are **less bound**.

Shift ist proportional to the

size of the proton

P states: zero at r=0

Electron is not inside the proton.

Orbital pictures from Wikipedia

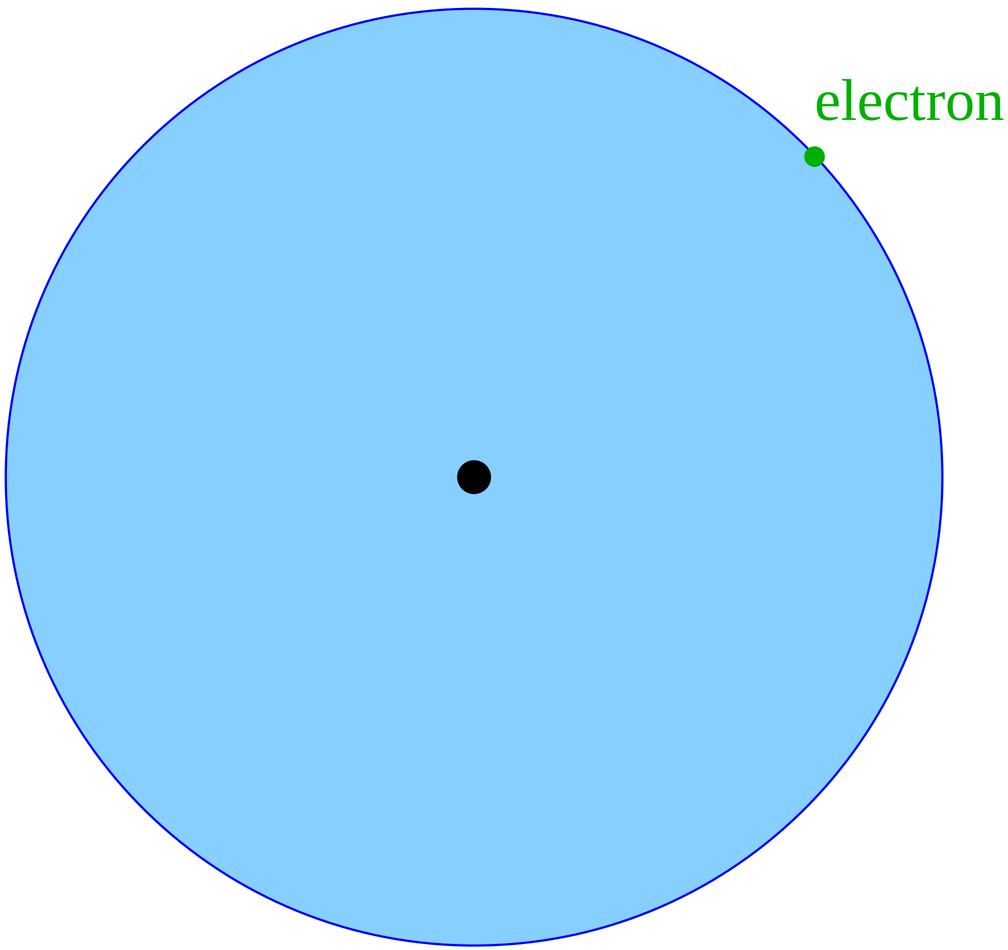
Muonic hydrogen

Regular hydrogen:

electron e^- + proton p

Muonic hydrogen:

muon μ^- + proton p



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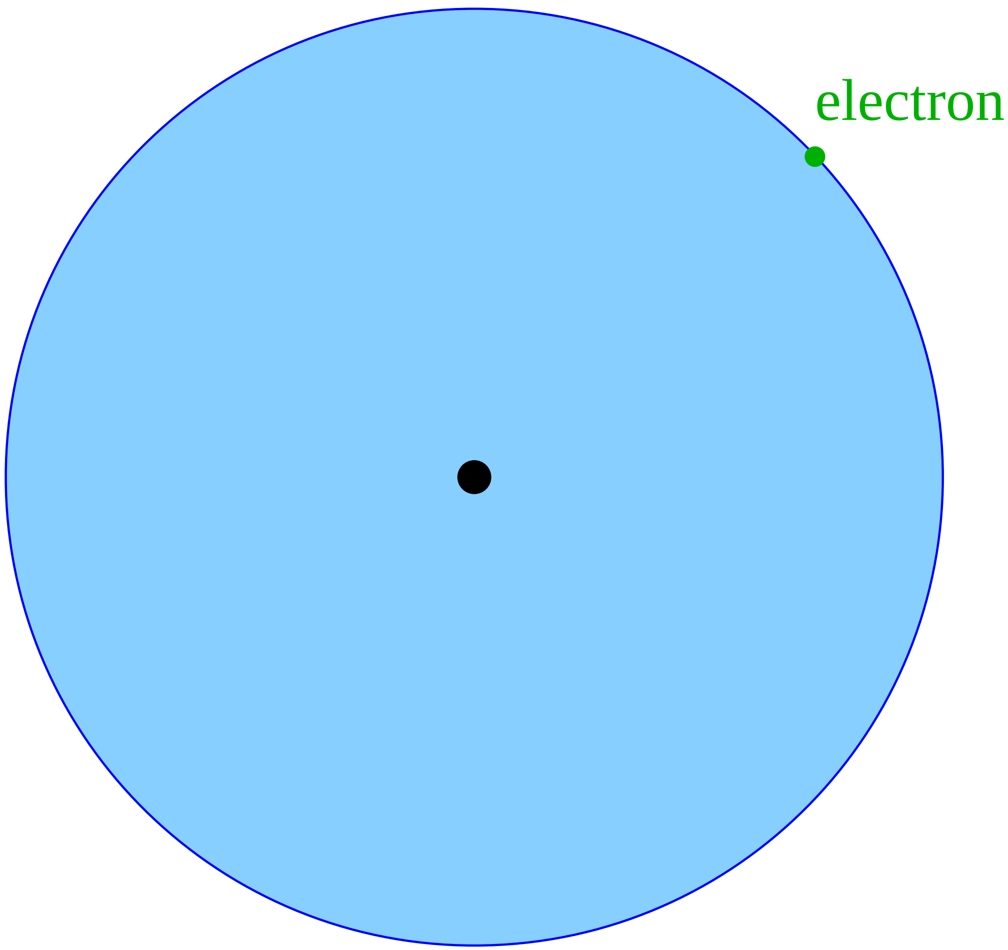

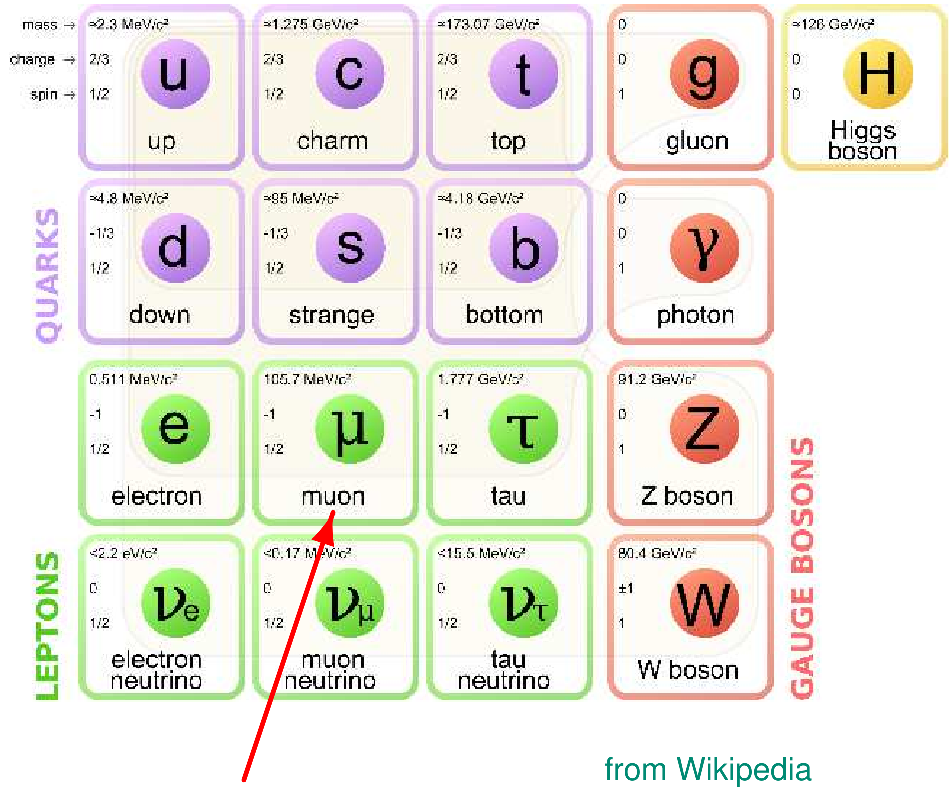

from Wikipedia

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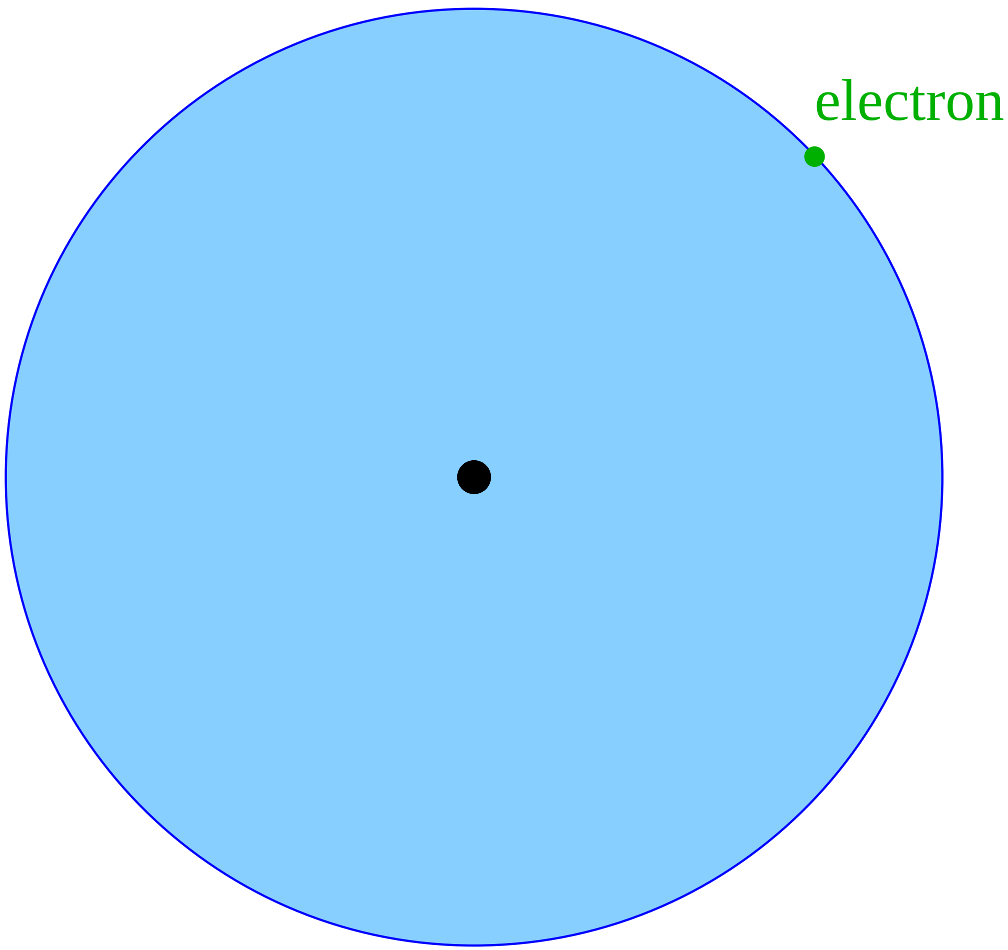


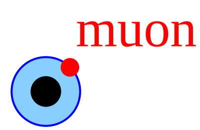
Muonic hydrogen:

muon μ^- + proton p

muon mass $m_\mu \approx 200 \times m_e$

Bohr radius $r_\mu \approx 1/200 \times r_e$

μ inside the proton: $200^3 \approx 10^7$



muon **much** is more sensitive to r_{p}

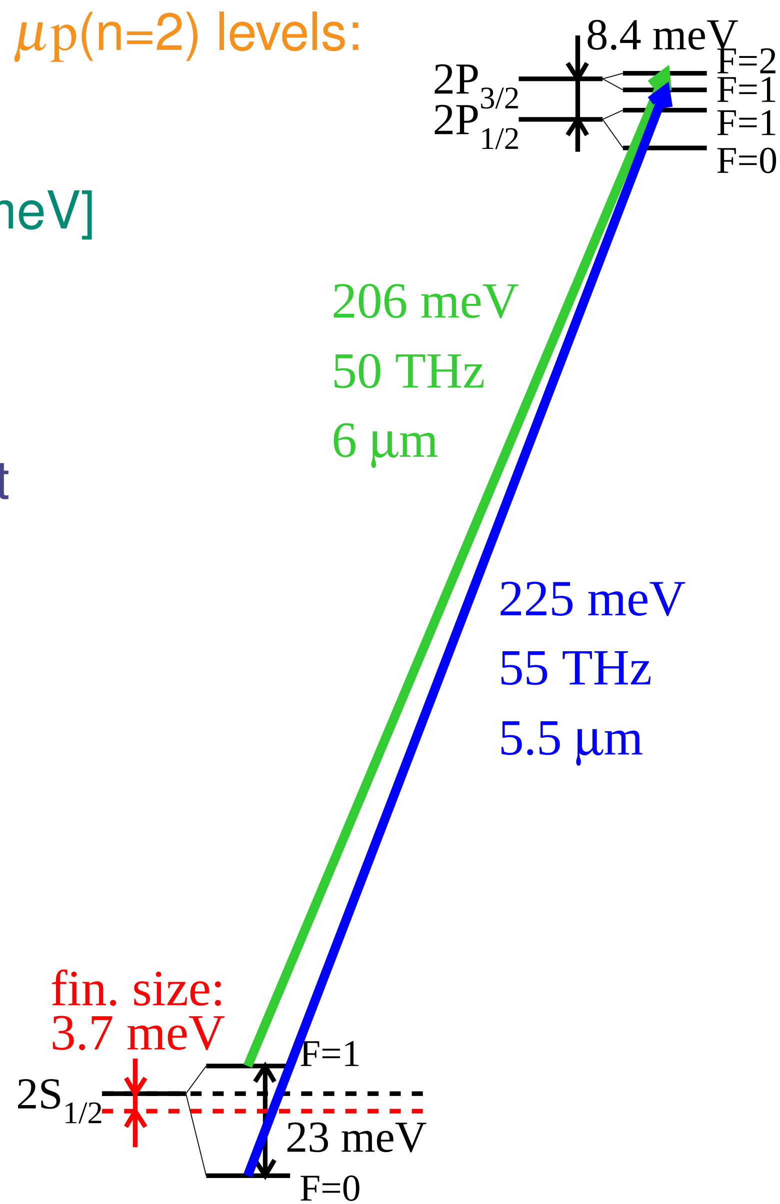
Proton charge radius and muonic hydrogen

Lamb shift in μp [meV]:

$$\Delta E = 206.0668(25) - 5.2275(10)\, r_p^2 \quad \text{[meV]}$$

Proton size effect is 2% of the μp Lamb shift

Measure to 10^{-5} $\Rightarrow$ r_p to 0.05 %



Experiment:

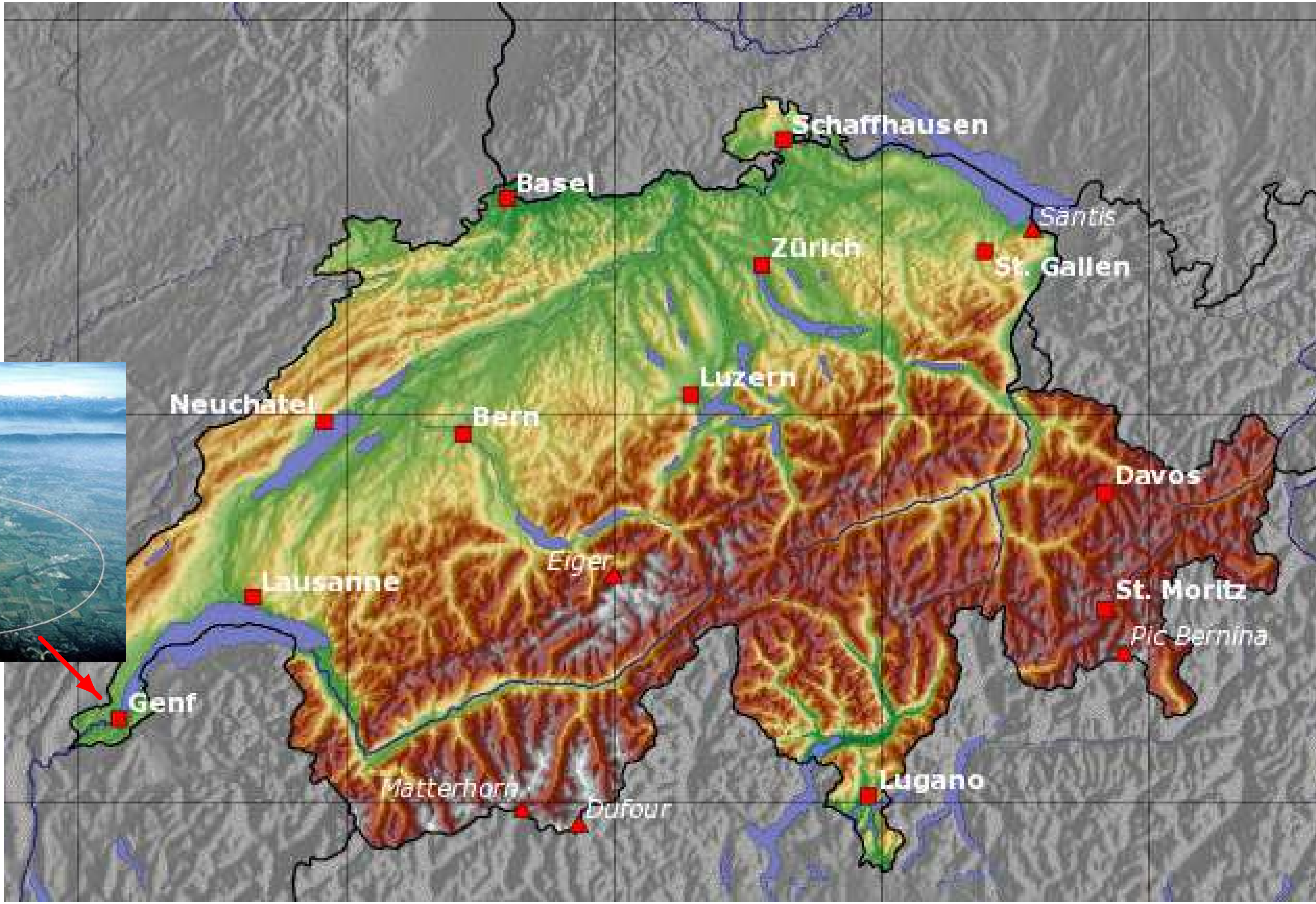
R. Pohl *et al.*, Nature 466, 213 (2010).

A. Antognini, RP *et al.*, Science 339, 417 (2013).

Theory summary:

A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013).

Swiss muons


Schaffhausen
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Säntis
Zürich
St. Gallen
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Bern
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Eiger
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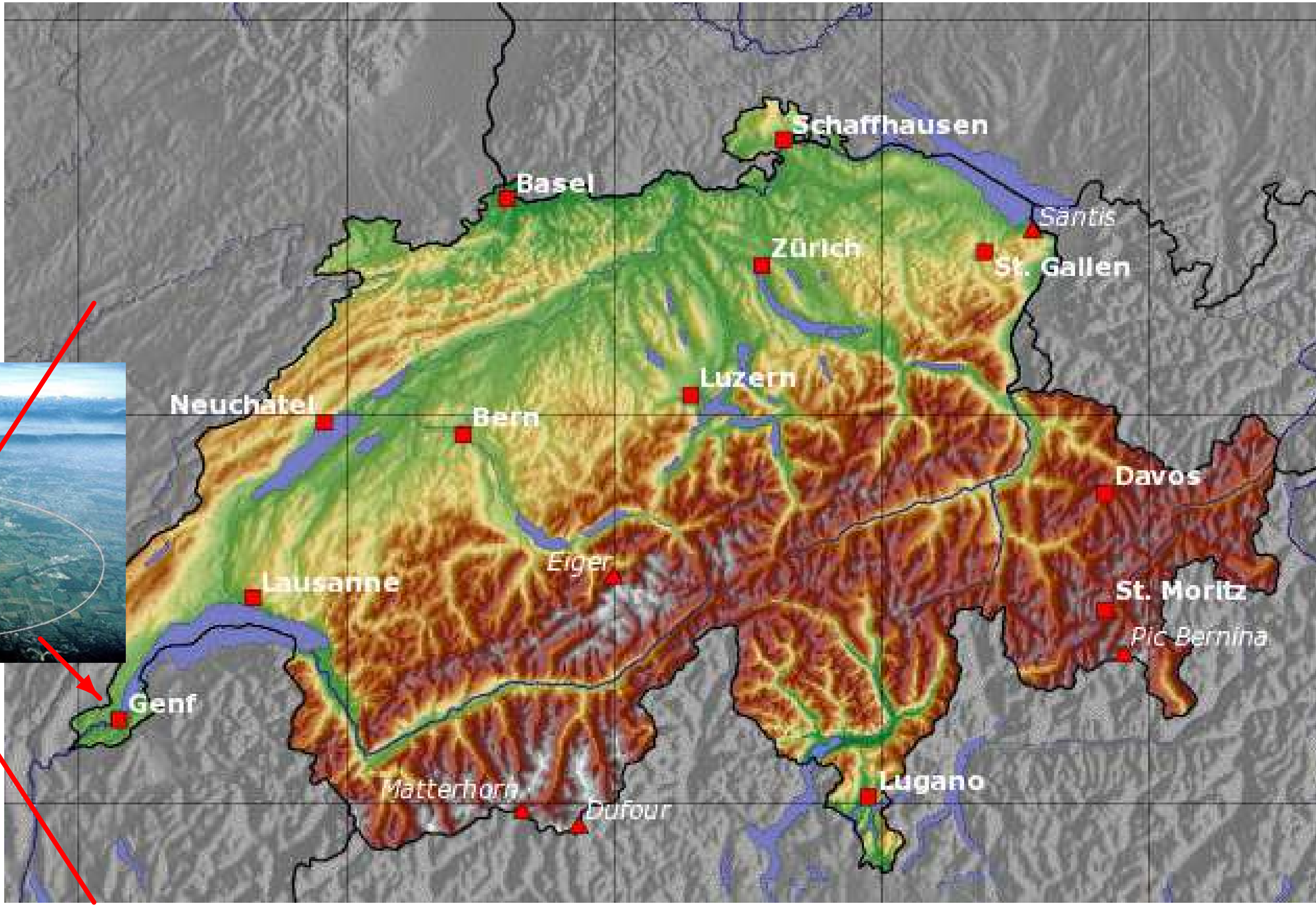
Genf
Lugano
Matterhorn
Dufour

Swiss muons


Schaffhausen
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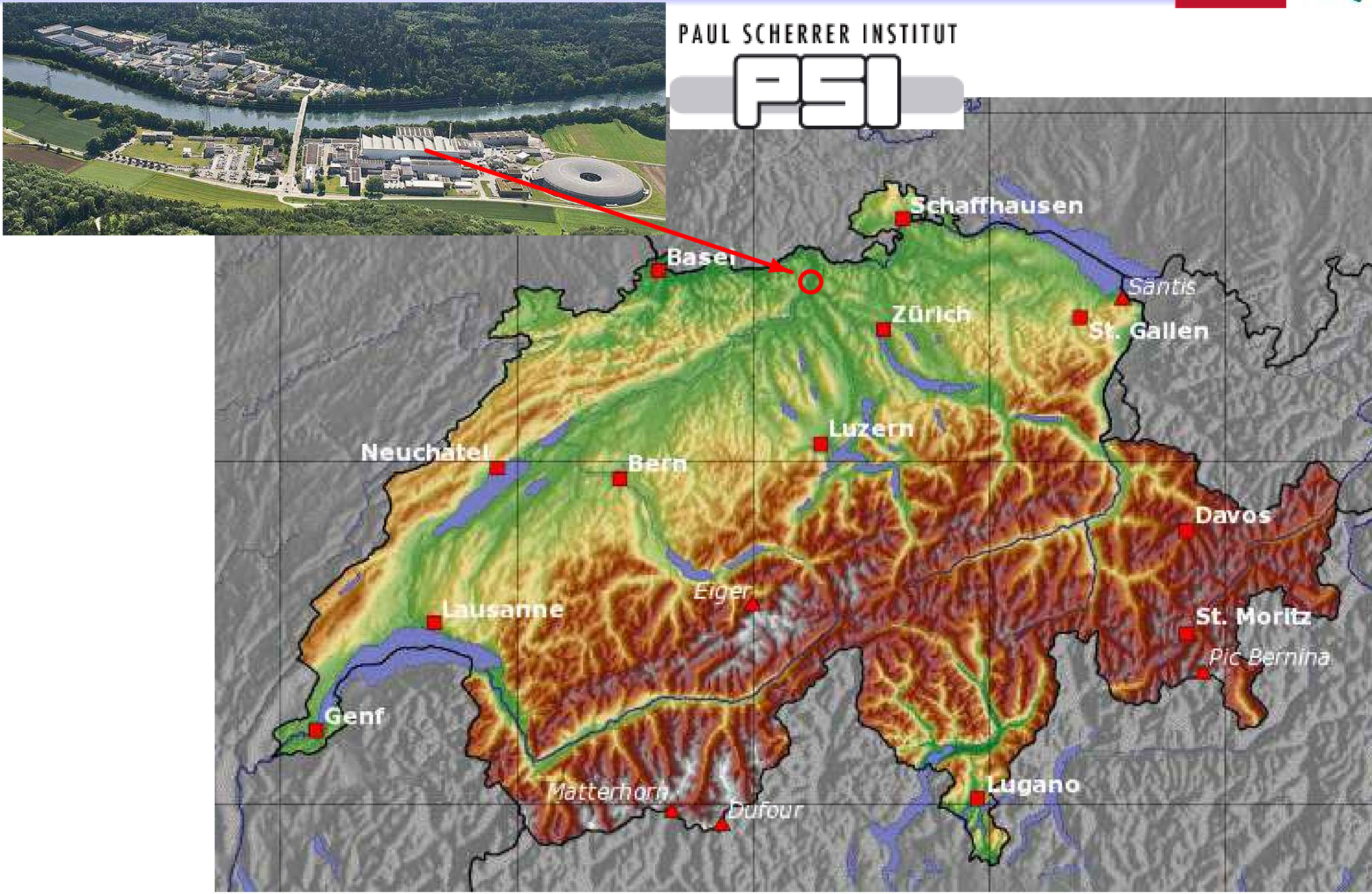
Matterhorn
Dufour

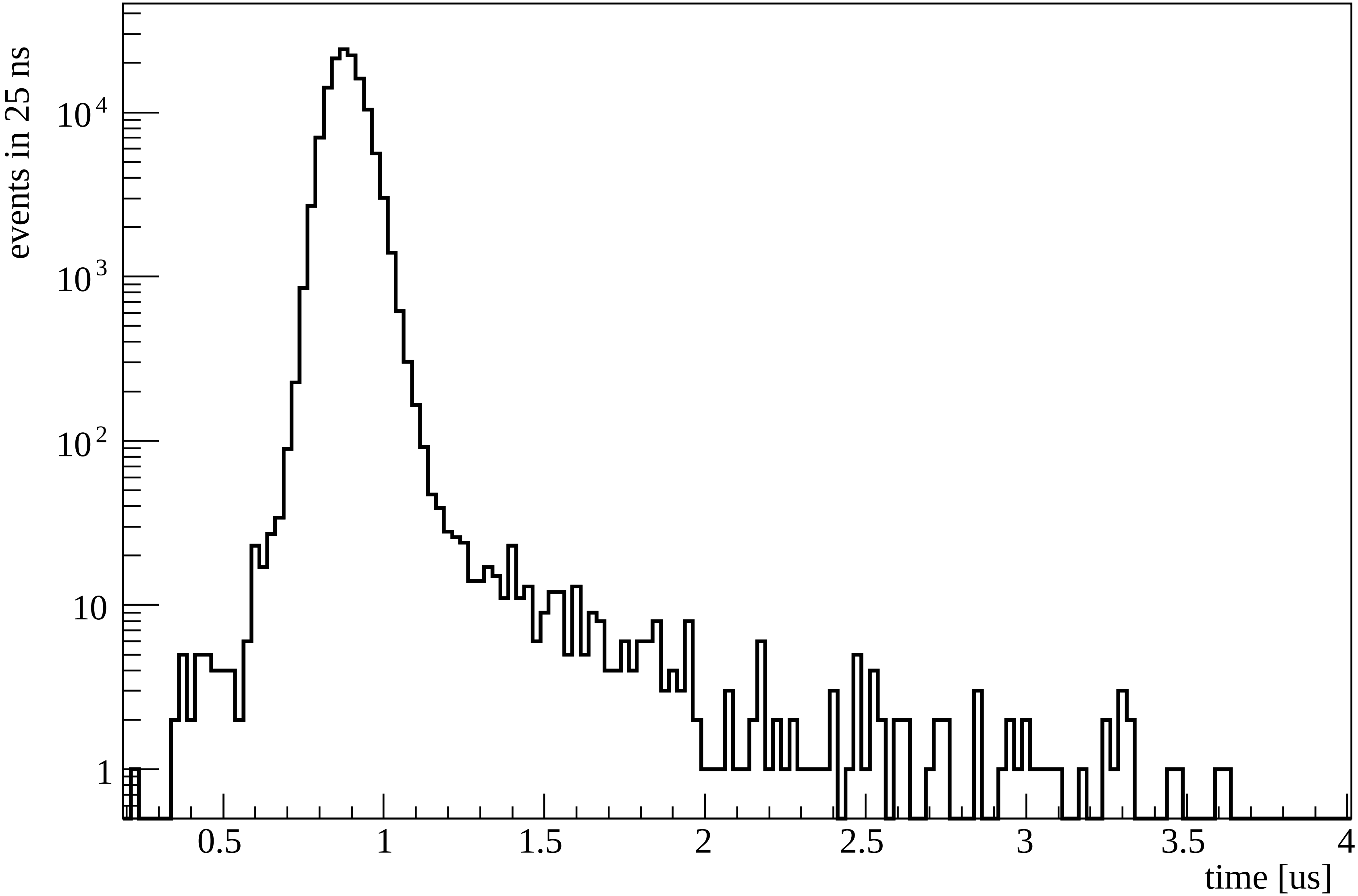
Swiss muons

PAUL SCHERRER INSTITUT



μp Lamb shift experiment: Principle

time spectrum of 2 keV x-rays (∼ 13 hours of data @ 1 laser wavelength)



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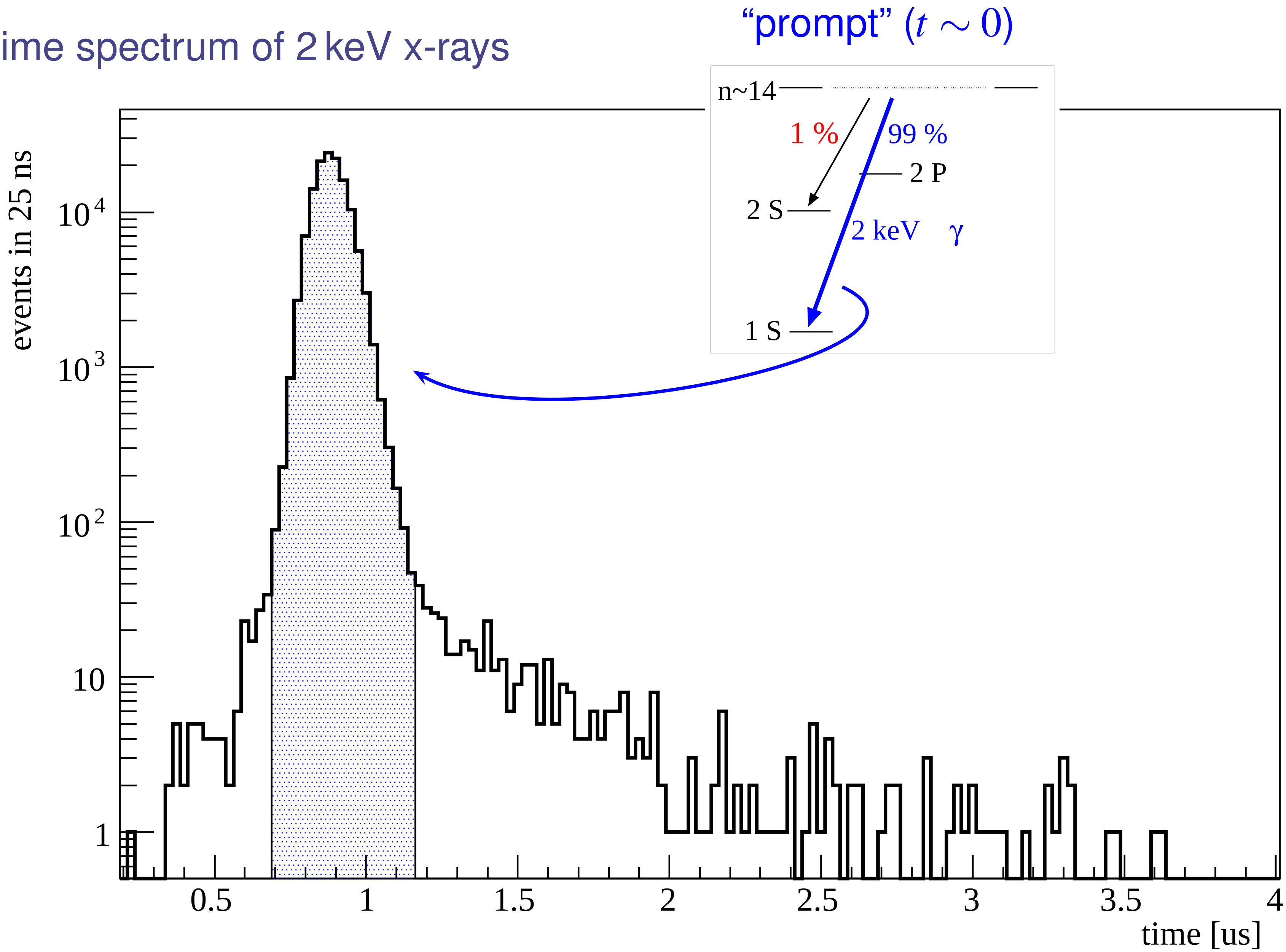

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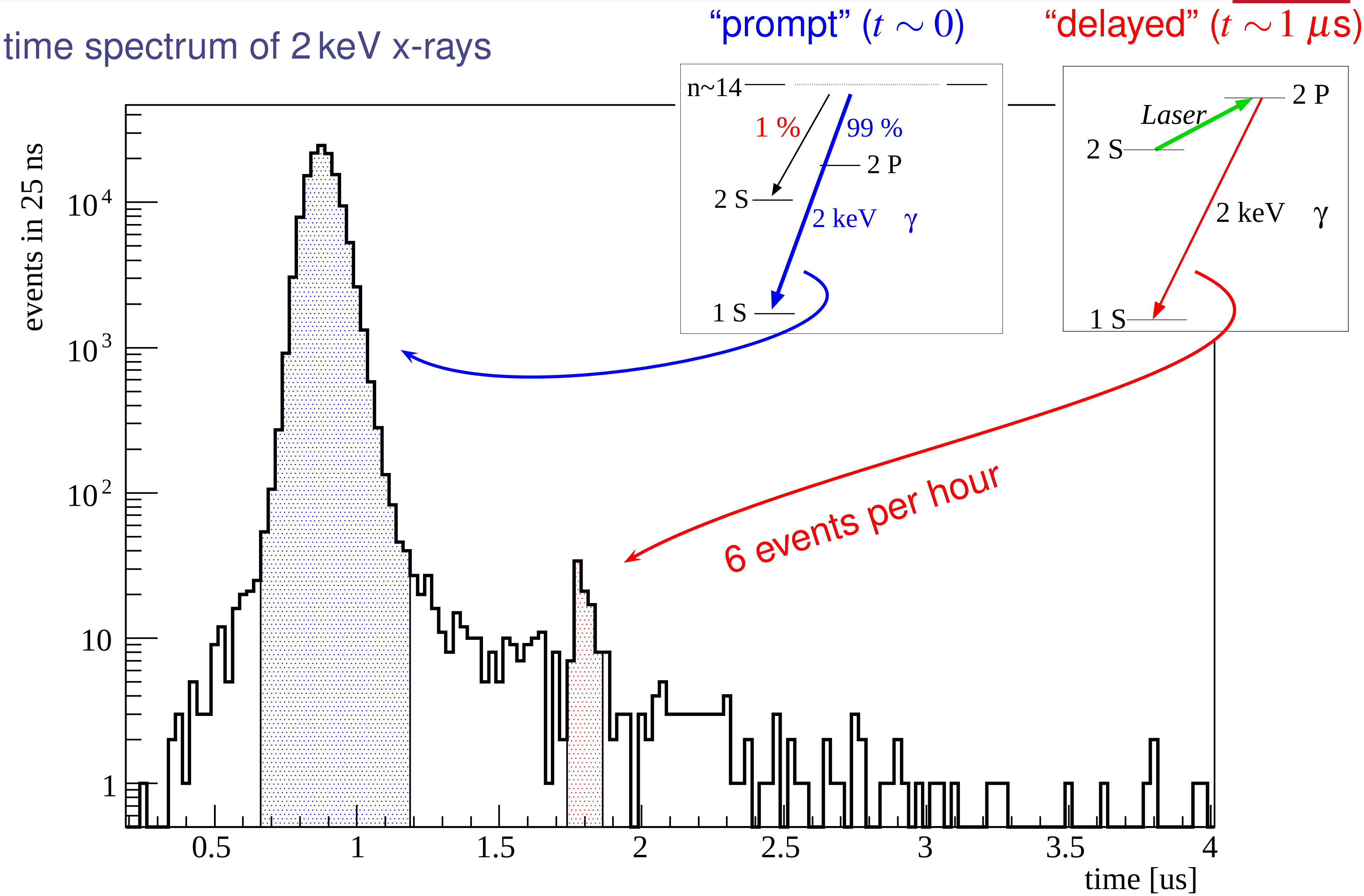

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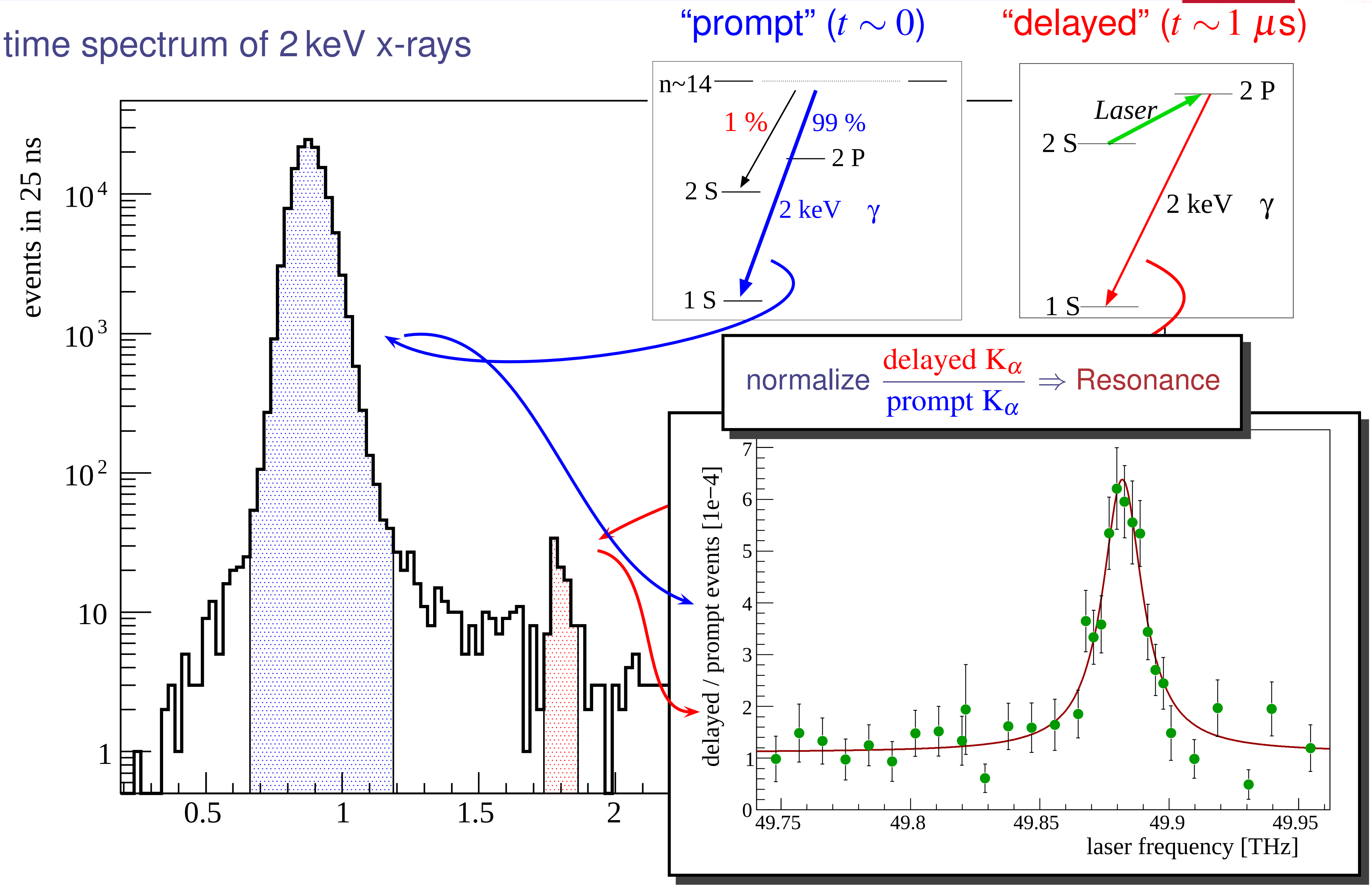
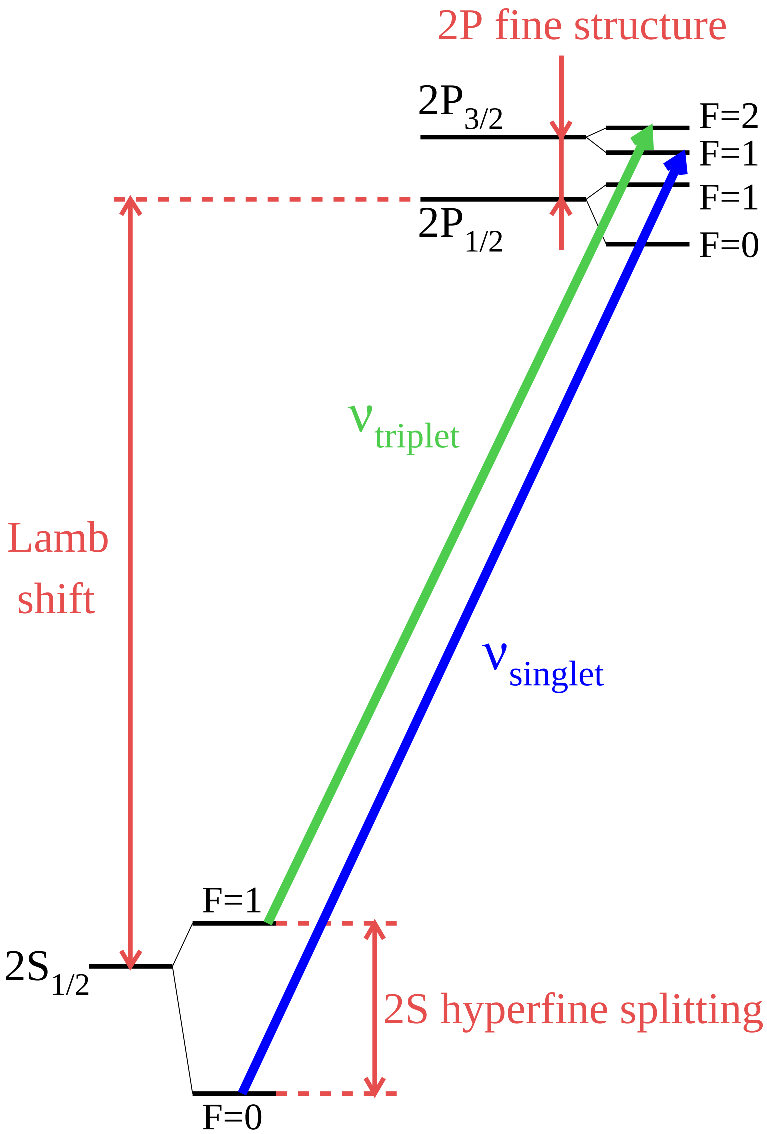
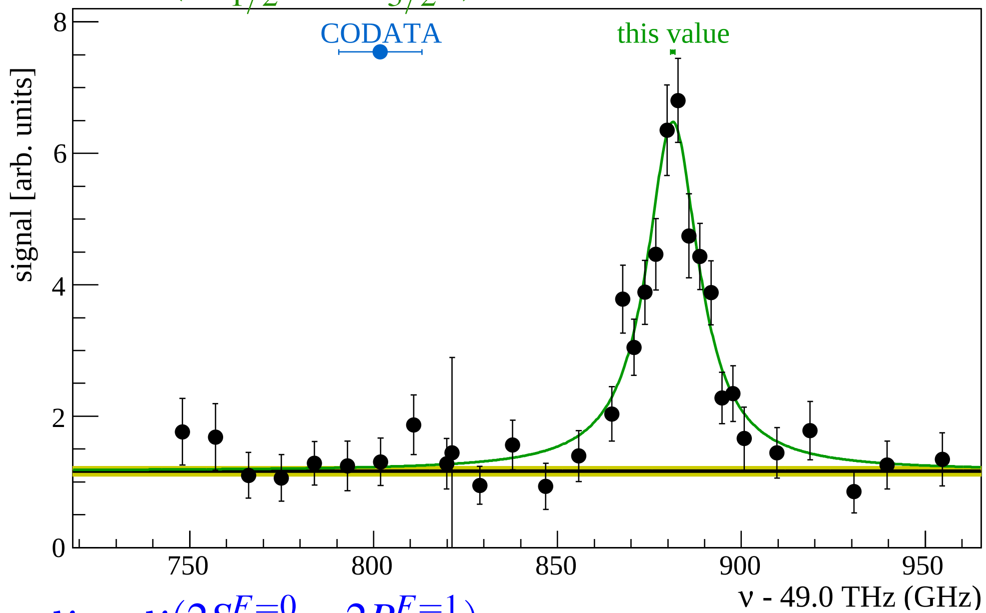


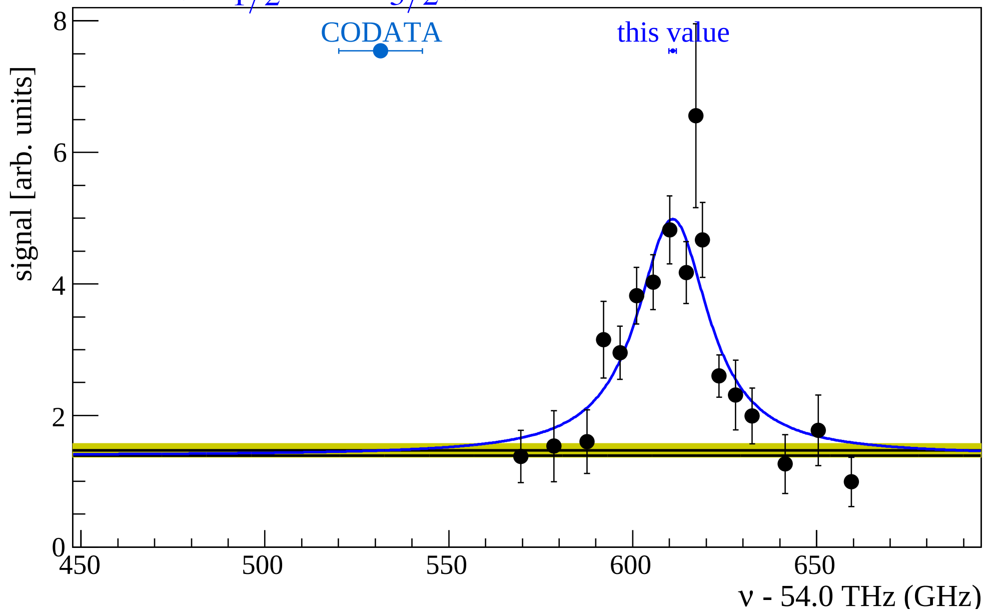
Muonic hydrogen results



$\nu_t = \nu(2S_{1/2}^{F=1} - 2P_{3/2}^{F=2})$



$\nu_s = \nu(2S_{1/2}^{F=0} - 2P_{3/2}^{F=1})$



Exp.: R. Pohl *et al.*, Nature 466, 213 (2010).
A. Antognini, RP *et al.*, Science 339, 417 (2013).

Theo: A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013).

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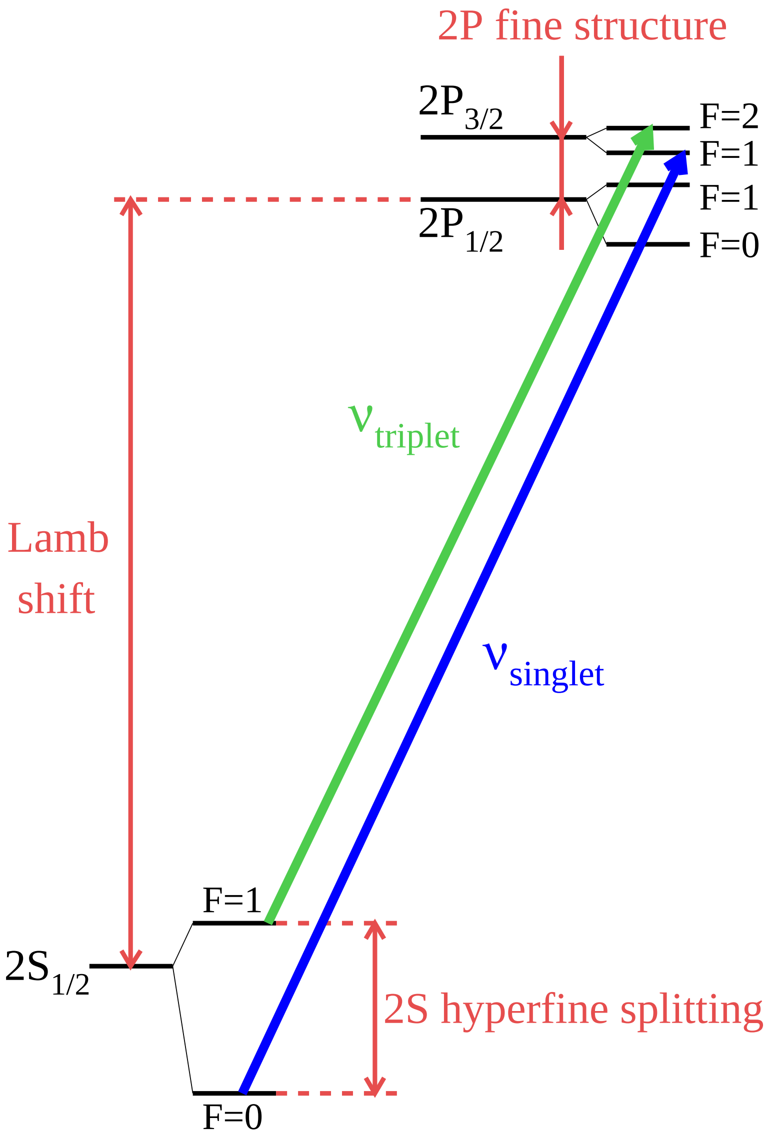

- two transitions measured

  ν_t = 49881.35(65) GHz

  ν_s = 54611.16(1.05) GHz

- Lamb shift ⇒ **charge radius**

$$\Delta E_{\rm LS} = 206.0668(25) - 5.2275(10)\, r_{\rm E}^2 \quad \text{[meV, fm]}$$

$$r_{\rm E}^2 = \int d^3r\, r^2\, \rho_E(r)$$

$$r_{\rm E} = 0.84087\,(26)_{\rm exp}\,(29)_{\rm th}\ \text{fm} = 0.84087\ (39)\ \text{fm}$$

10x more precise than CODATA-2010
4% smaller (7σ)
proton radius puzzle

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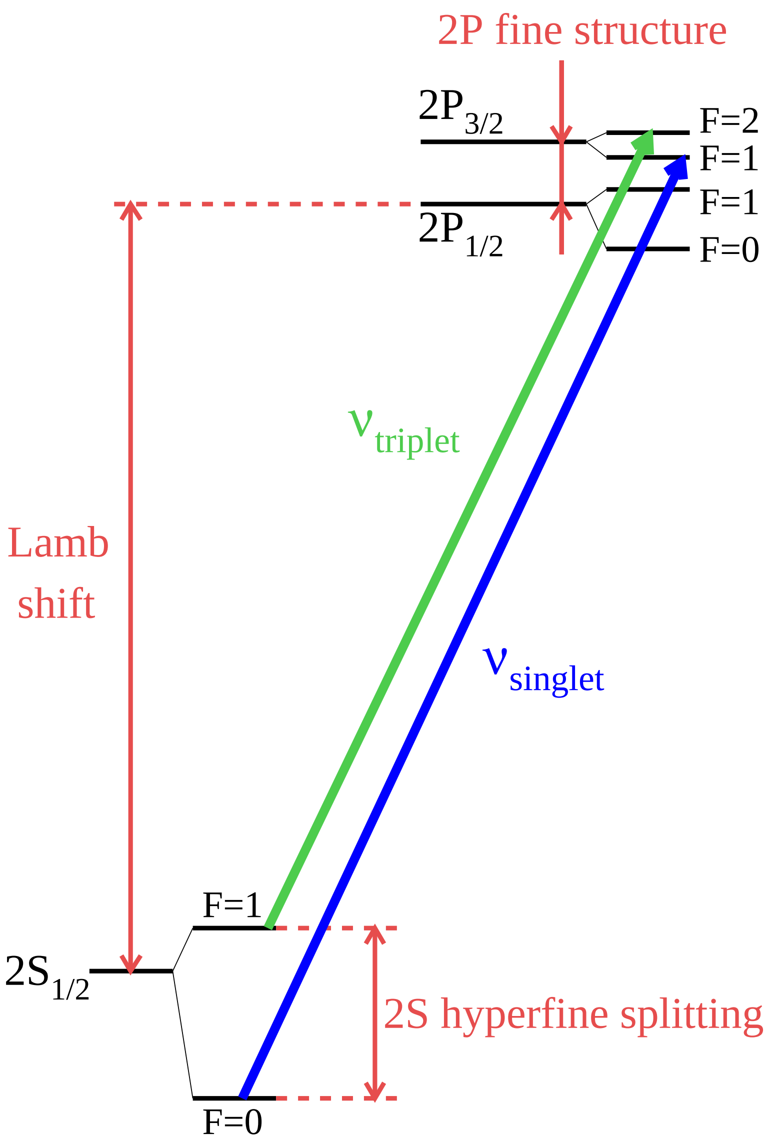

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- 2S-HFS ⇒ **Zemach radius**

$$\Delta E_{HFS} = 22.9843(30) - 0.1621(10)\, r_Z \quad \text{[meV, fm]}$$

$$r_Z = \int d^3r \int d^3r'\ r\, \rho_E(r)\, \rho_M(r - r')$$

$$r_Z = 1.082\ (31)_{exp}\ (20)_{th}\ \text{fm} = 1.082\ (37)\ \text{fm}$$

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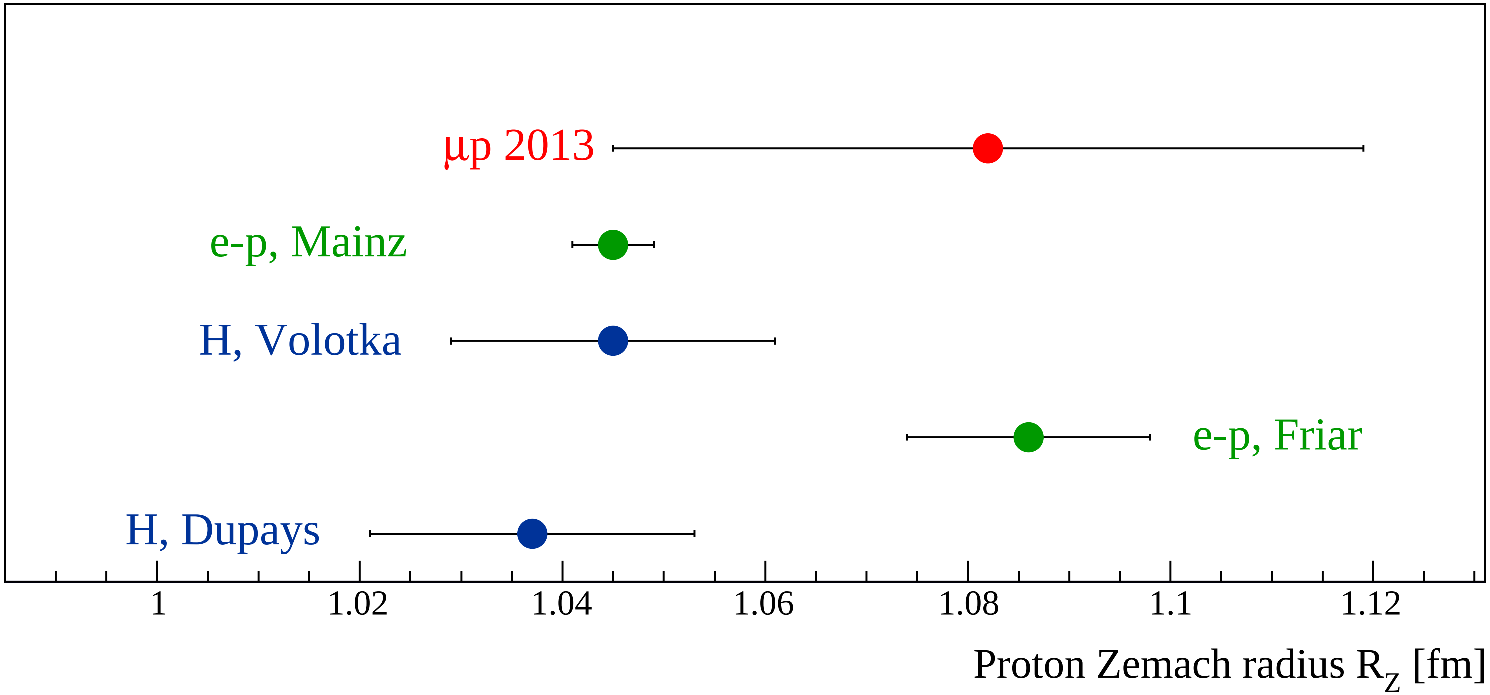
Proton Zemach radius

2S hyperfine splitting in μp is: $\Delta E_{\mathrm{HFS}} = 22.9843(30) - 0.1621(10)\, r_Z\, [\mathrm{fm}]$ meV

with $r_Z = \int d^3r \int d^3r'\; r\, \rho_E(r)\, \rho_M(r - r')$

We measured $\Delta E_{\mathrm{HFS}} = 22.8089(51)$ meV

This gives a proton Zemach radius $r_Z = 1.082\ (31)_{\mathrm{exp}}\ (20)_{\mathrm{th}} = 1.082\ (37)$ fm



A. Antognini, RP *et al.*, Science 339, 417 (2013)

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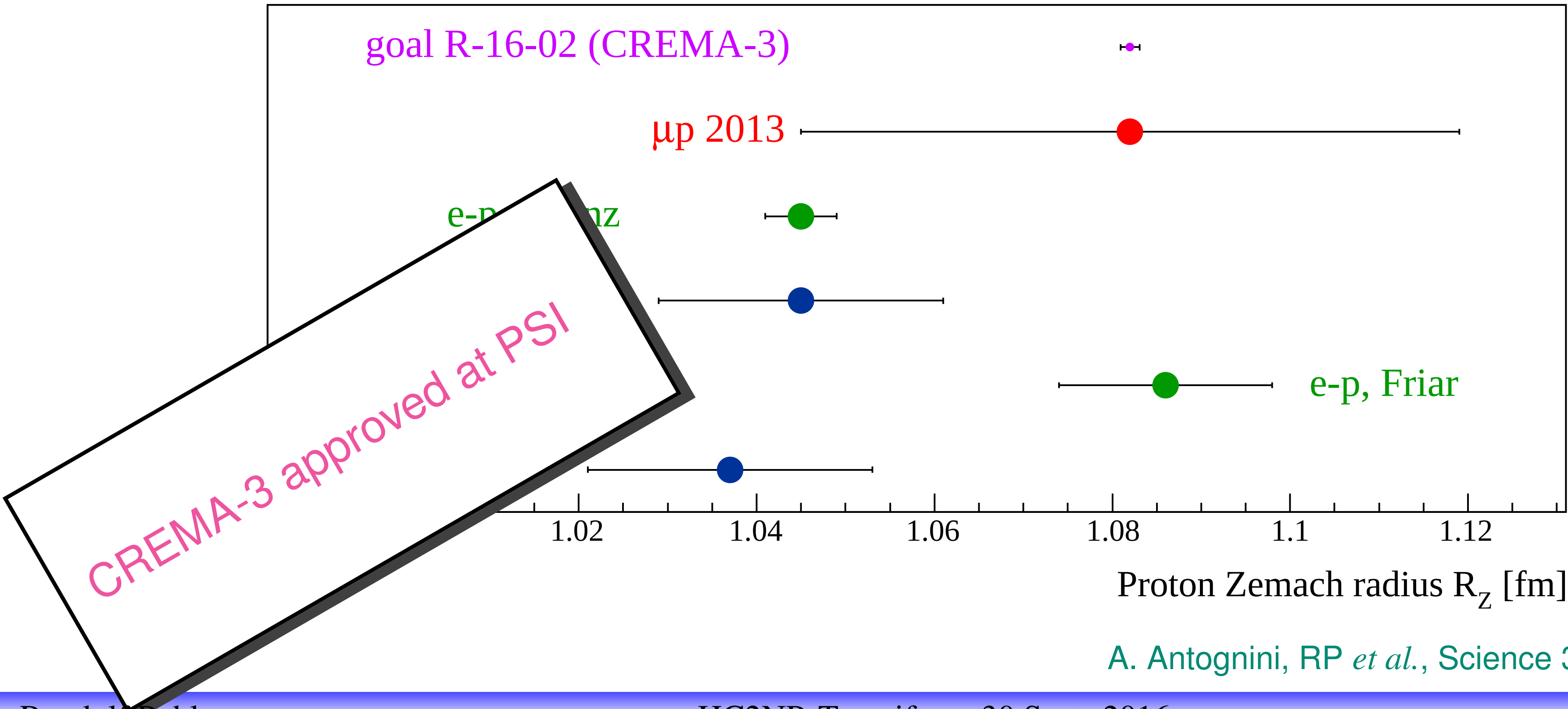
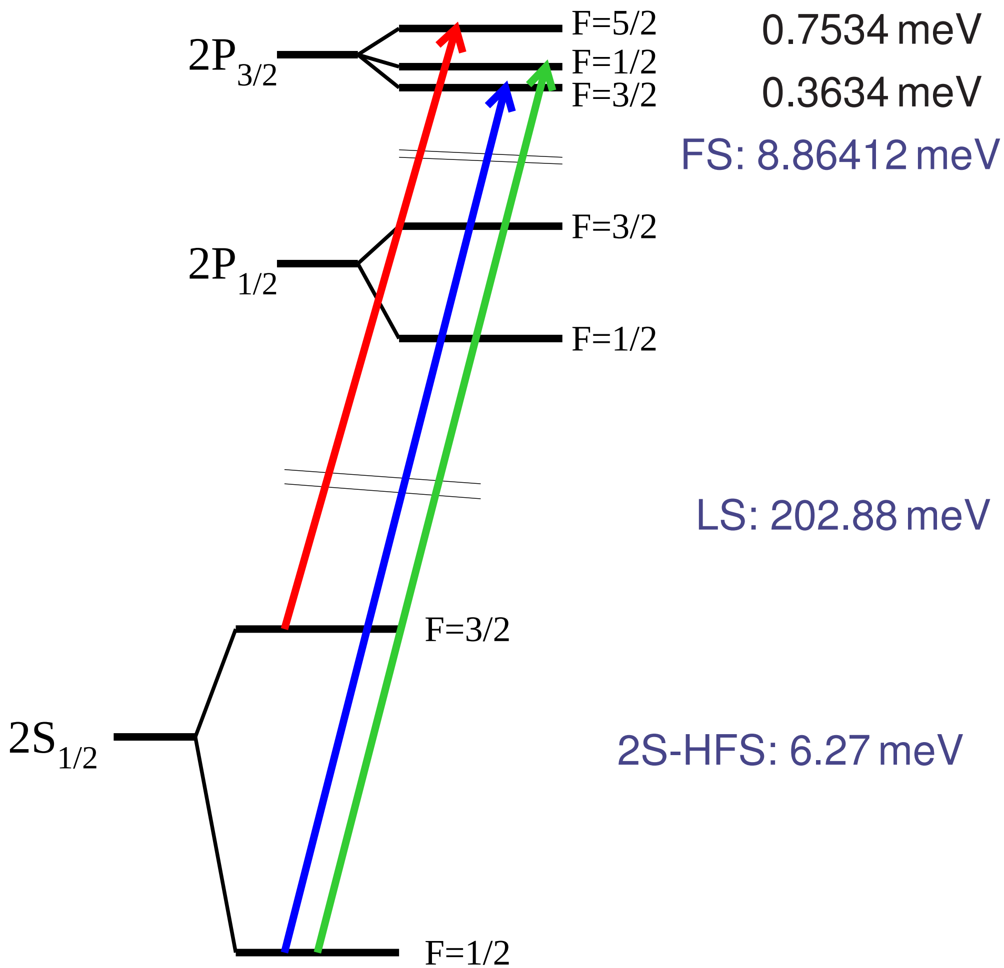
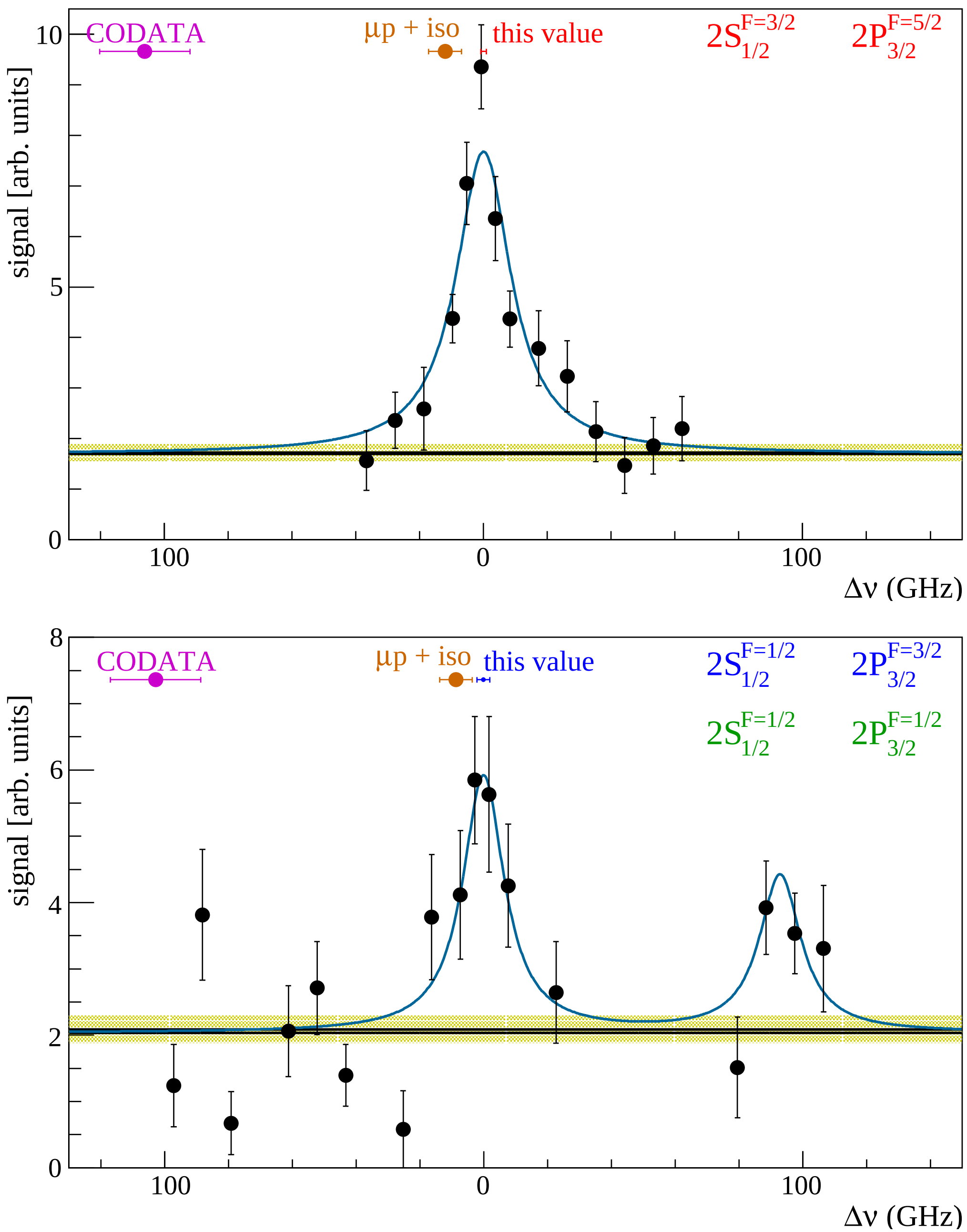


A. Antognini, RP *et al.*, Science 339, 417 (2013)

Muonic deuterium



Muonic DEUTERIUM

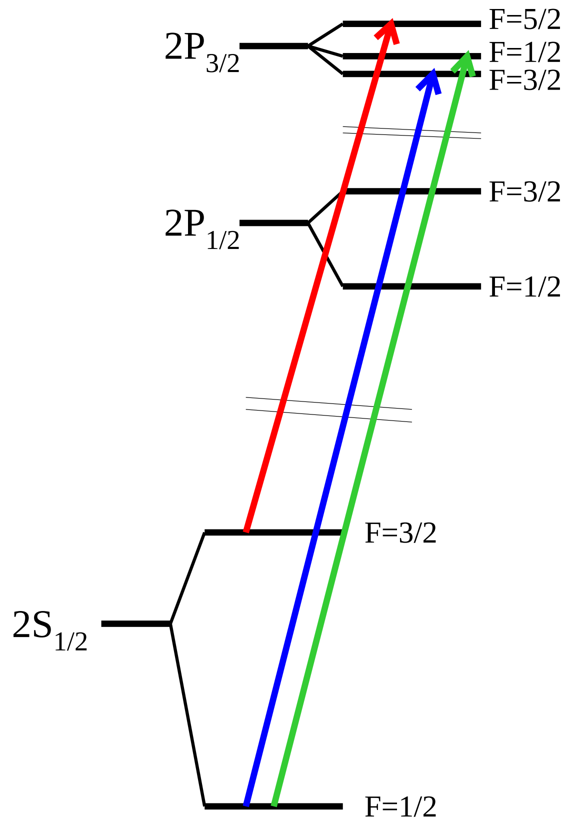


Experiment:

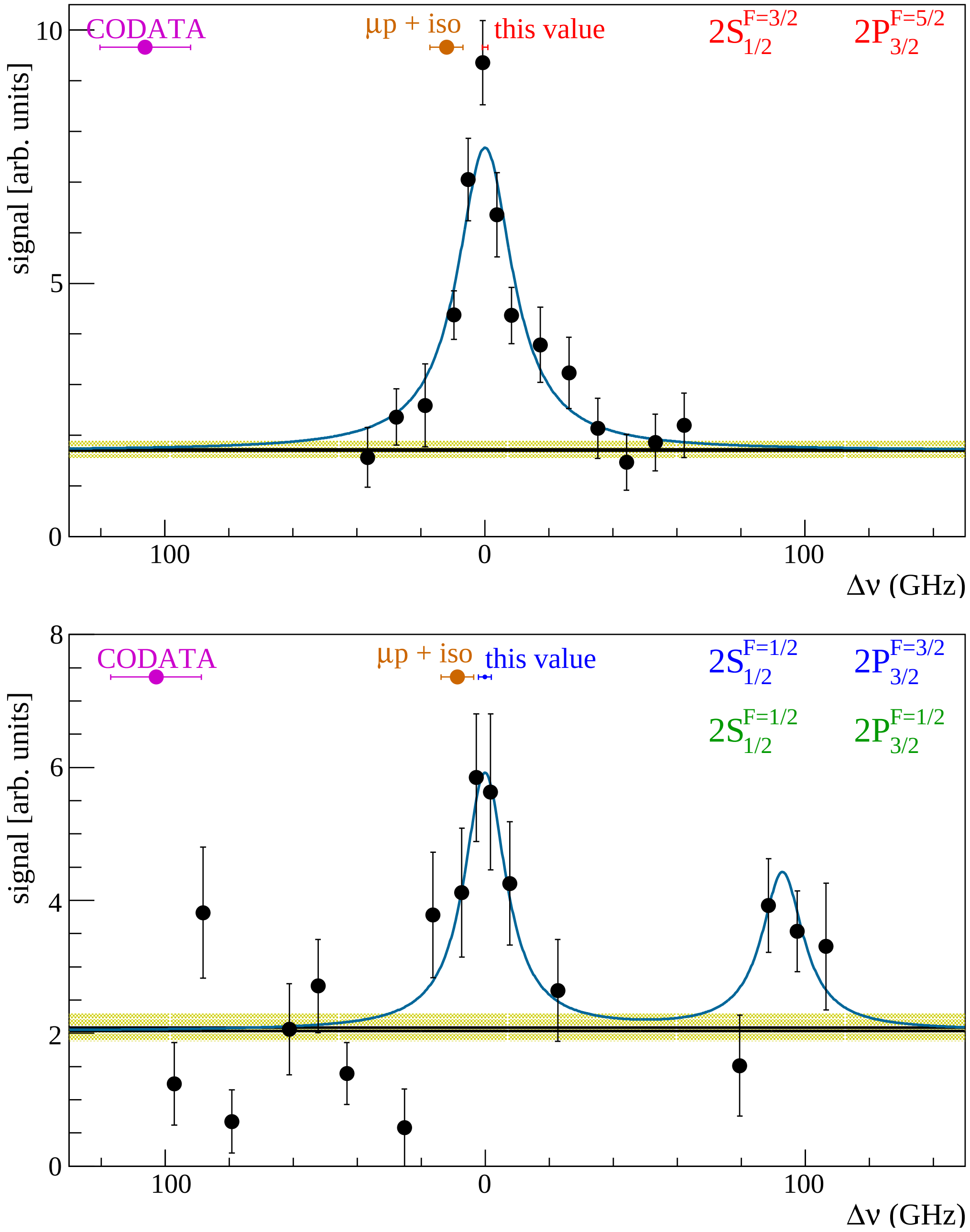
RP *et al.* (CREMA), Science **353**, 417 (2016).

$$\Delta E_{LS}^{exp} = 202.8785\,(31)_{stat}\,(14)_{syst} \text{ meV}$$

$$\Rightarrow r_d = 2.12562(13)_{exp}(77)_{theo} \text{ fm}$$



Muonic DEUTERIUM



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Theory:

$$\Delta E_{LS}^{theo} = 228.7766(\ \ 10)\,\text{meV}\ (\text{QED})$$
$$+1.7096(200)\,\text{meV}\ (\text{TPE})$$
$$-6.1103(\ \ \ 3)\,r_d^2\,\text{meV}/\text{fm}^2,$$

Krauth, RP *et al.*, Ann. Phys. **366**, 168 (2016) [arXiv 1506.01298]

based on papers and communication from

Bacca, Barnea, Birse, Borie, Carlson, Eides, Faustov, Friar, Gorchtein, Hernandez, Ivanov, Jentschura, Ji, Karshenboim, Korzinin, Krutov, Martynenko, McGovern, Nevo Dinur, Pachucki, Shelyuto, Sick, Vanderhaeghen *et al.*

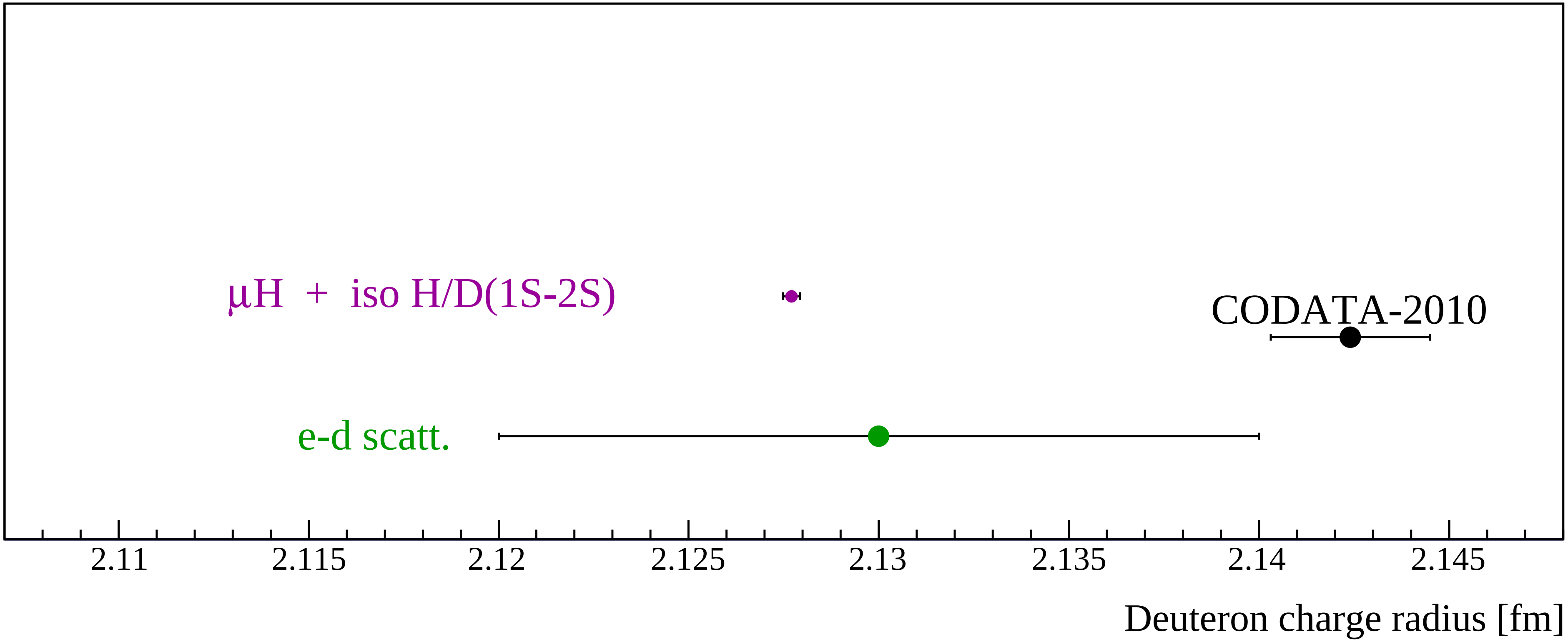
THANK YOU!

Deuteron charge radius

H/D isotope shift: $r_d^2 - r_p^2 = 3.82007(65)$ fm^2 C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)

CODATA 2010 $r_d = 2.14240(210)$ fm

r_p from μH gives $r_d = 2.12771(\ 22)$ fm $\leftarrow 7\sigma$ from r_p



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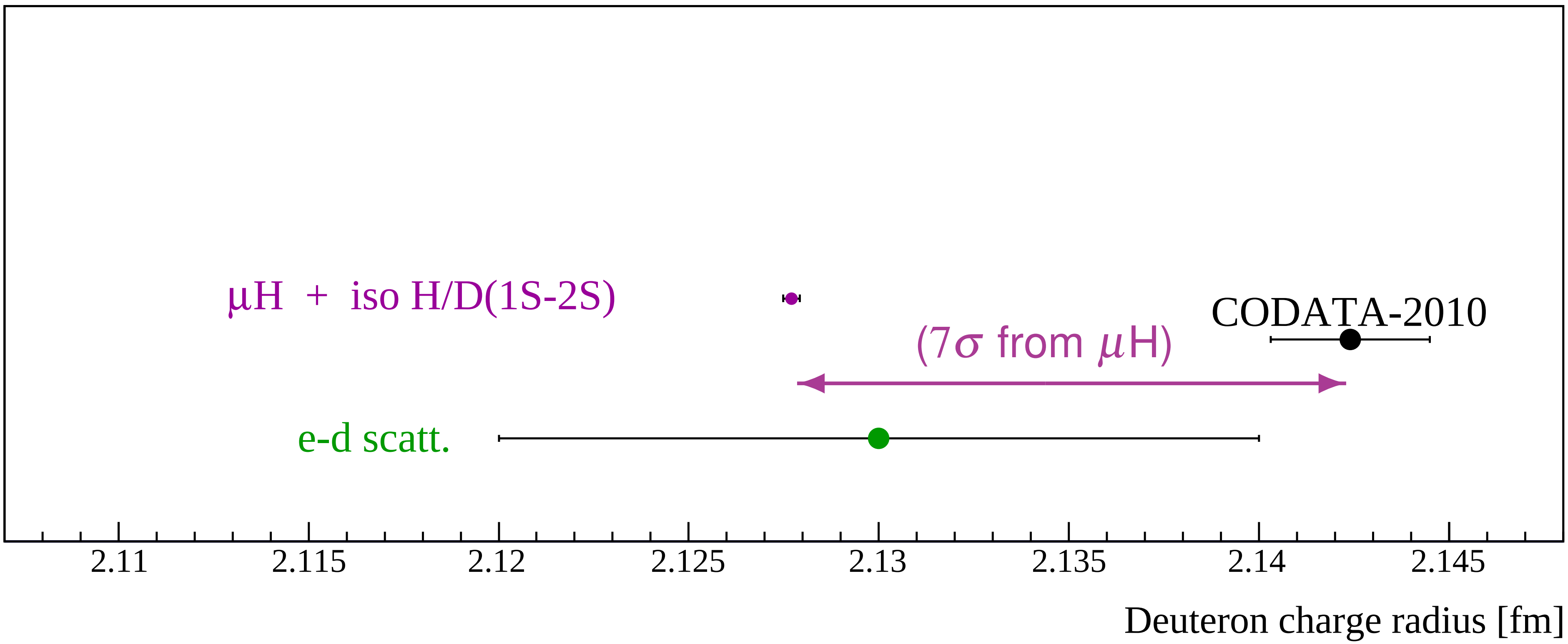

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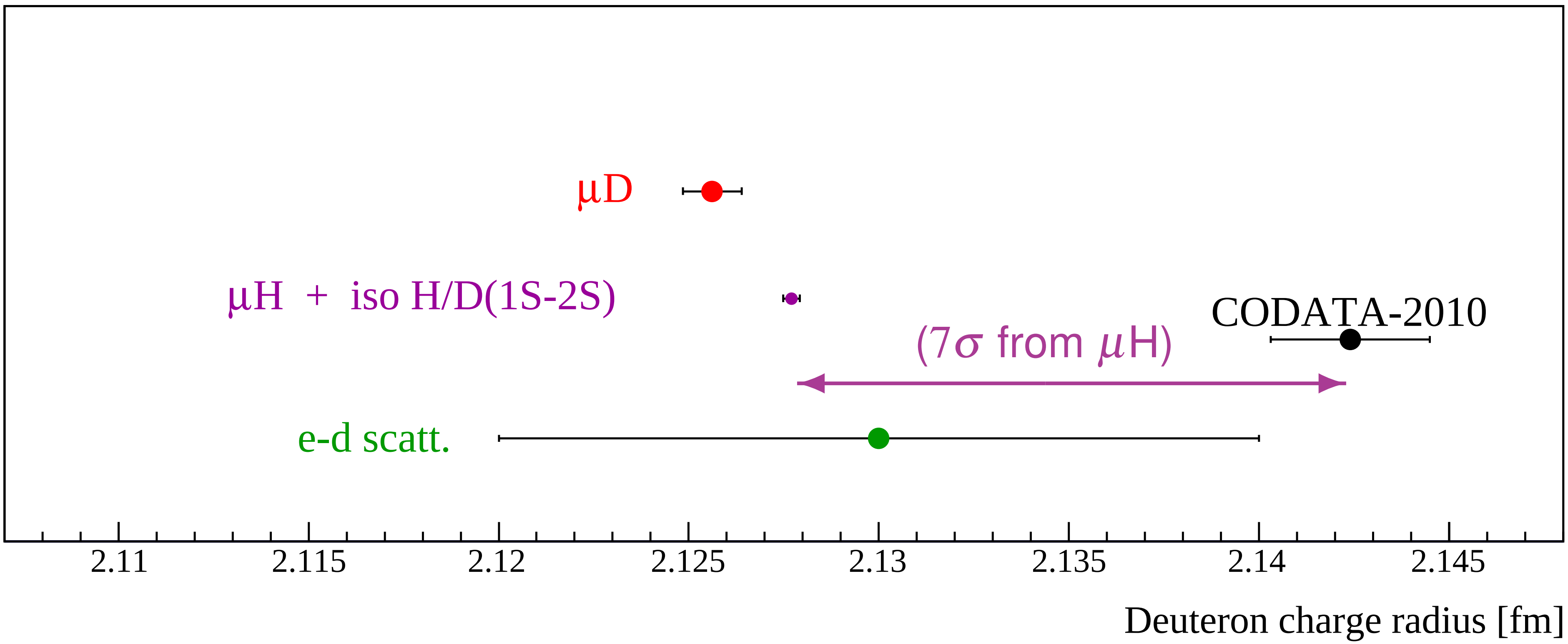

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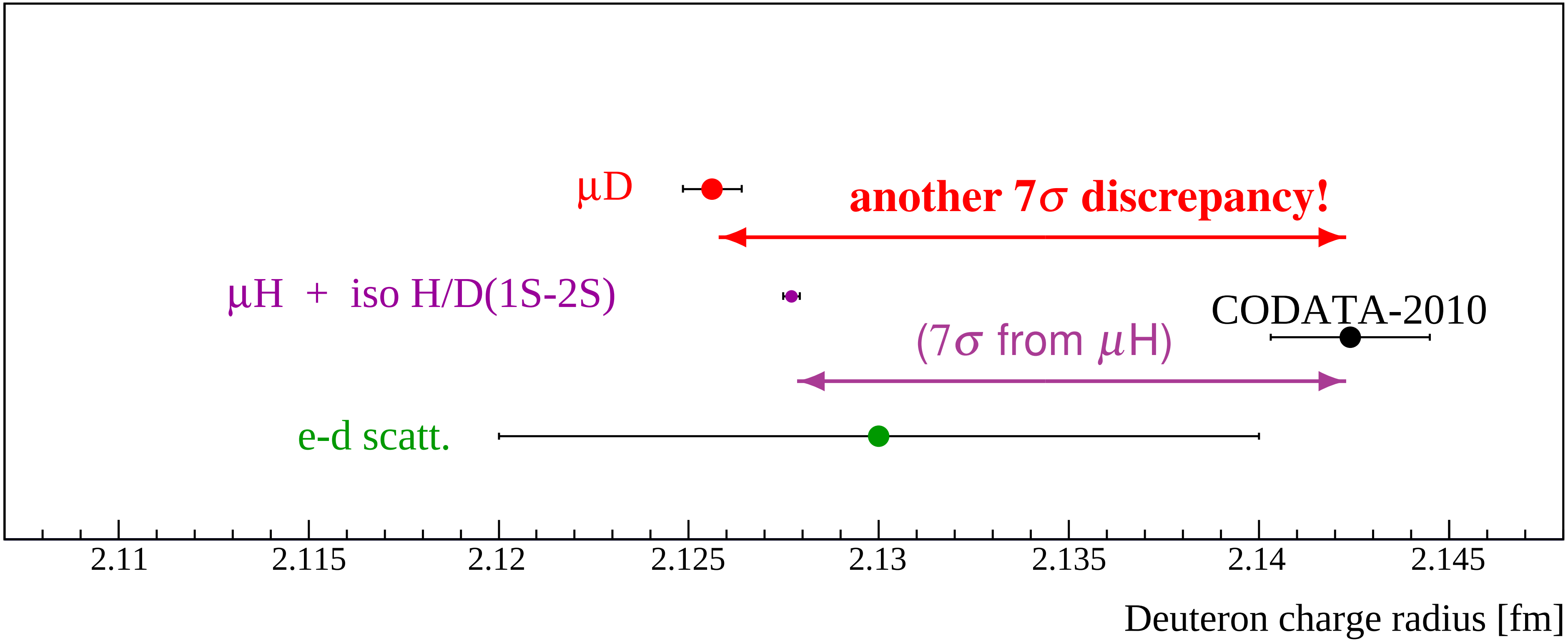

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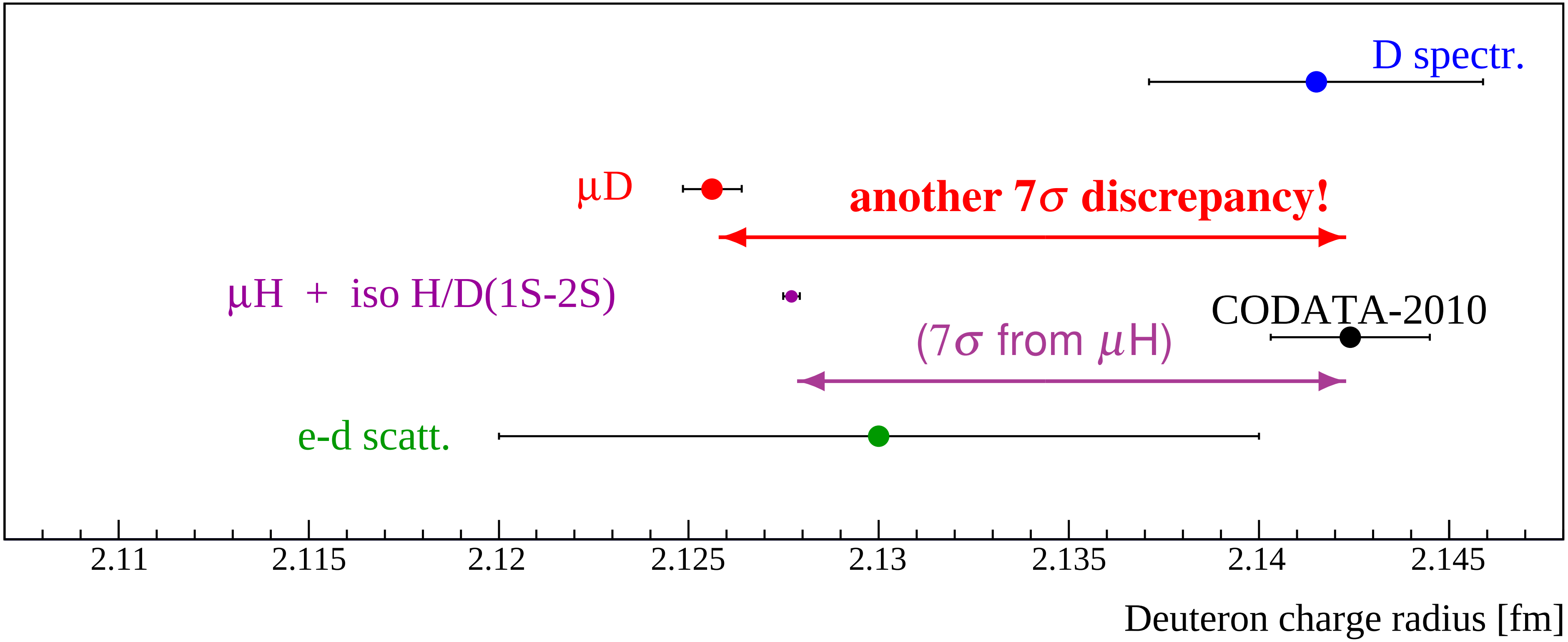
electronic D (r_p indep.)	$r_d = 2.14150(450)$ fm	RP *et al.* arXiv 1607.03165



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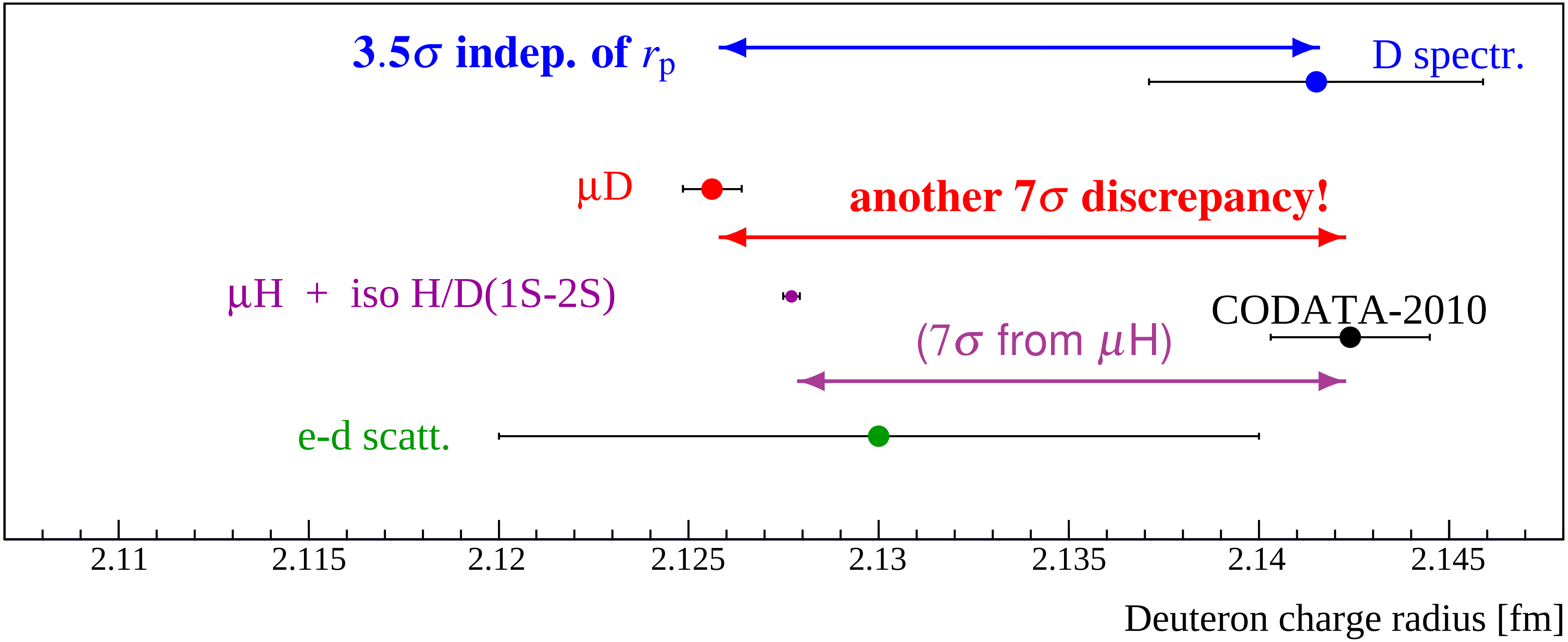
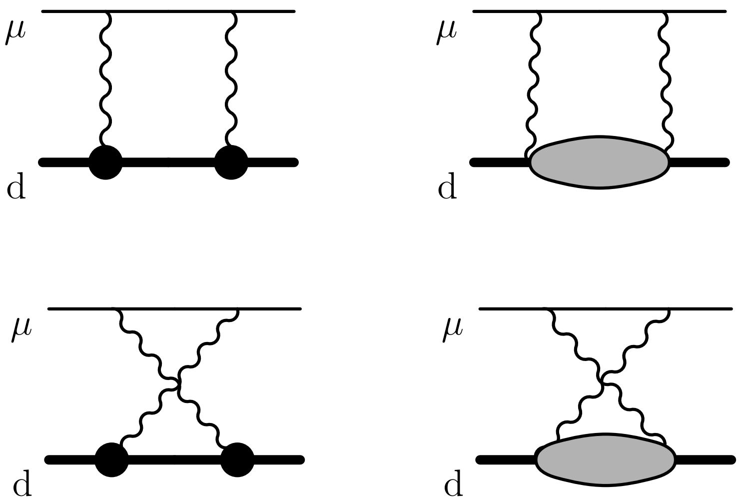


Theory in μd: TPE

$r_{\rm d} = 2.12562(13)_{\rm exp}(77)_{\rm theo}$ fm,   using $\Delta E^{\rm theo}_{\rm TPE} = 1.7096(200)$ meV

limited by **deuteron structure** (TPE) contributions to the μd LS



Cancellation between elastic “Friar” (a.k.a. 3rd Zemach) terms and part of inelastic “polarizability” contributions.

Nucleon structure adds relevant contributions (and uncertainty).

Friar & Payne, PRA 56, 5173 (1997) ; Pachucki, PRL 106, 193007 (2011) ; Friar, PRC 88, 034003 (2013) ;
Hernandez *et al.*, PLB 736, 344 (2014) ; Pachucki & Wienczek, PRA 91, 040503(R) (2015) ;
Carlson, Gorchtein, Vanderhaeghen, PRA 89, 022504 (2014) ; Birse & McGovern *et al.*

J.J. Krauth, RP *et al.*, Ann. Phys. **366**, 168 (2016) [1506.01298]

Theory in μd: TPE

Table 3: Deuteron structure contributions to the Lamb shift in muonic deuterium. Values are in meV.

Item	Contribution	Pachucki [55]		Friar [60]		Hernandez *et al.* [58]			Pach.& Wienczek [65]		Carlson *et al.* [64]	Our choice		
		AV18		ZRA		AV18	N^{3}LO †		AV18		data	value		source
	Source	1		2		3	4		5		6			
p1	Dipole	1.910	$\delta_0 E$	1.925	Leading C1	1.907	1.926	$\delta_{D1}^{(0)}$	1.910	$\delta_0 E$		1.9165	± 0.0095	3-5
p2	Rel. corr. to p1, longitudinal part	−0.035	$\delta_R E$	−0.037	Subleading C1	−0.029	−0.030	$\delta_L^{(0)}$	−0.026	$\delta_R E$				
p3	Rel. corr. to p1, transverse part					0.012	0.013	$\delta_T^{(0)}$						
p4	Rel. corr. to p1, higher order								0.004	$\delta_{HO} E$				
sum	Total rel. corr., p2+p3+p4	−0.035		−0.037		−0.017	−0.017		−0.022			−0.0195	± 0.0025	3-5
p5	Coulomb distortion, leading	−0.255	$\delta_{C1} E$						−0.255	$\delta_{C1} E$				
p6	Coul. distortion, next order	−0.006	$\delta_{C2} E$						−0.006	$\delta_{C2} E$				
sum	Total Coulomb distortion, p5+p6	−0.261				−0.262	−0.264	$\delta_C^{(0)}$	−0.261			−0.2625	± 0.0015	3-5
p7	El. monopole excitation	−0.045	$\delta_{Q0} E$	−0.042	C0	−0.042	−0.041	$\delta_{R2}^{(2)}$	−0.042	$\delta_{Q0} E$				
p8	El. dipole excitation	0.151	$\delta_{Q1} E$	0.137	Retarded C1	0.139	0.140	$\delta_{D1D3}^{(2)}$	0.139	$\delta_{Q1} E$				
p9	El. quadrupole excitation	−0.066	$\delta_{Q2} E$	−0.061	C2	−0.061	−0.061	$\delta_Q^{(2)}$	−0.061	$\delta_{Q2} E$				
sum	Tot. nuclear excitation, p7+p8+p9	0.040		0.034	C0 + ret-C1 + C2	0.036	0.038		0.036			0.0360	± 0.0020	2-5
p10	Magnetic	−0.008 ◇	$\delta_M E$	−0.011	M1	−0.008	−0.007	$\delta_M^{(0)}$	−0.008	$\delta_M E$		−0.0090	± 0.0020	2-5
SUM_1	Total nuclear (corrected)	1.646		1.648		1.656	1.676		1.655			1.6615	± 0.0103	
p11	Finite nucleon size			0.021	Retarded C1 f.s.	0.020 ◇	0.021 ◇??	$\delta_{NS}^{(2)}$	0.020	$\delta_{FS} E$				
p12	n p charge correlation			−0.023	pn correl. f.s.	−0.017	−0.017	$\delta_{np}^{(1)}$	−0.018	$\delta_{FZ} E$				
sum	p11+p12			−0.002		0.003	0.004		0.002			0.0010	± 0.0030	2-5
p13	Proton elastic 3rd Zemach moment	} 0.043(3)	$\delta_P E$	0.030	$\langle r^3\rangle_{(2)}^{pp}$				} 0.043(3)	$\delta_P E$		0.0289	± 0.0015	Eq.(13)
p14	Proton inelastic polarizab.					} 0.027(2)		$\delta_{\rm pol}^N$ [64]			} 0.028(2) $\Delta E^{\rm hadr}$	} 0.0280	± 0.0020	6
p15	Neutron inelastic polarizab.								0.016(8)	$\delta_N E$				
p16	Proton & neutron subtraction term											−0.0098	± 0.0098	Eq.(15)
sum	Nucleon TPE, p13+p14+p15+p16	0.043(3)		0.030		0.027(2)			0.059(9)			0.0471	± 0.0101	
SUM_2	Total nucleon contrib.	0.043(3)		0.028		0.030(2)			0.061(9)			0.0476	± 0.0105	
	Sum, published	1.680(16)		1.941(19)		1.690(20)			1.717(20)		2.011(740)			
	Sum, corrected			1.697(19)		1.714(20)			1.707(20)		1.748(740)	**1.7096**	**± 0.0147**	

J.J. Krauth *et al.*, Ann. Phys. **366**, 168 (2016) [1506.01298]

$$\Delta E^{\rm TPE}(\text{theo}) = 1.7096 \pm 0.0200 \text{ meV}$$

$$\Delta E^{\rm TPE}(\text{exp}) = 1.7638 \pm 0.0068 \text{ meV}$$

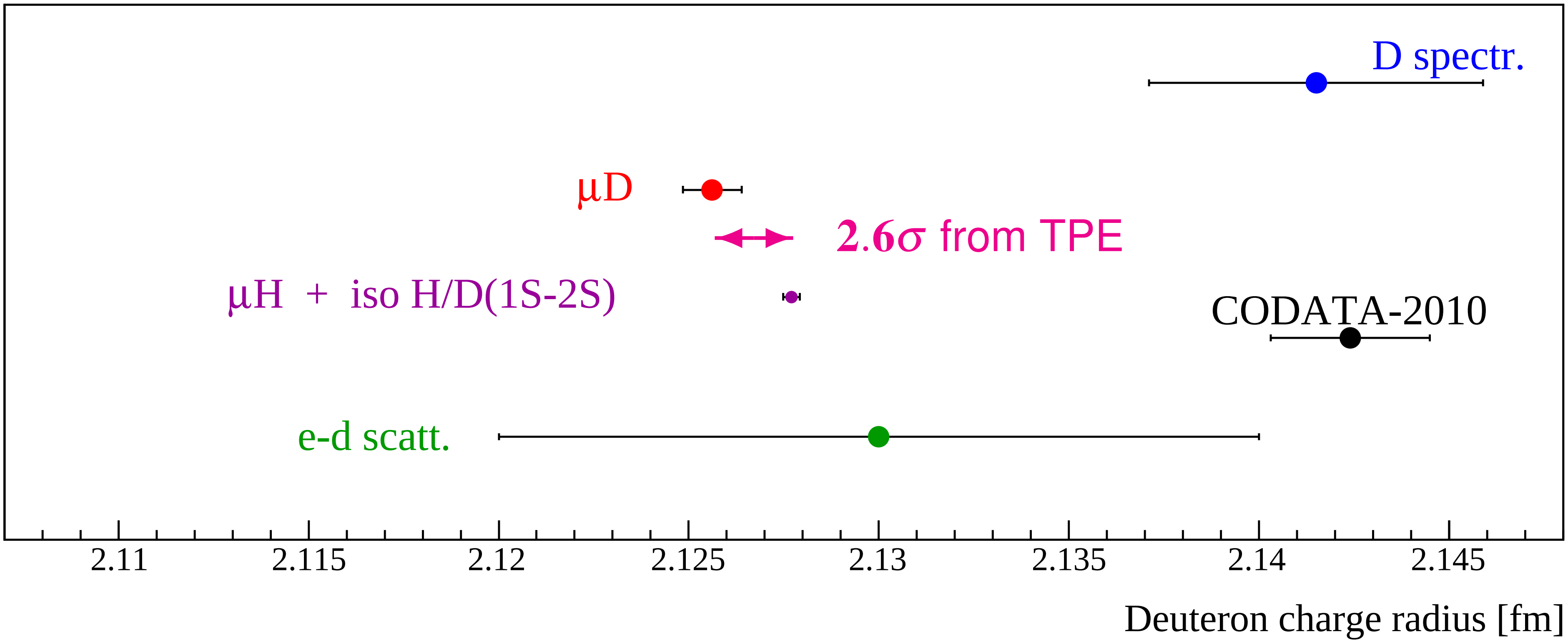
Experimental TPE in μd

$\Delta E^{\rm TPE}({\rm theo}) = 1.7096 \pm 0.0200$ meV

$\Delta E^{\rm TPE}({\rm exp}) = 1.7638 \pm 0.0068$ meV   **2.6σ**, 3x more accurate

$$\Delta E_{\rm LS} = 228.7766(10)\,{\rm meV}\ ({\rm QED}) + \Delta E^{\rm TPE} - 6.1103(3)\ r_{\rm d}^2\ {\rm meV/fm^2},$$

- $\Delta E_{\rm LS}^{\rm exp} = 202.8785\,(31)_{\rm stat}(14)_{\rm syst}$ meV from μD exp.
- $r_d = 2.12771(22)$ fm   from $r_{\rm d}^2 - r_{\rm p}^2 = 3.82007(65)$ fm^2 [H/D(1S-2S) isotope shift] using $r_{\rm p}(\mu{\rm H})$ = 0.84087(39) fm



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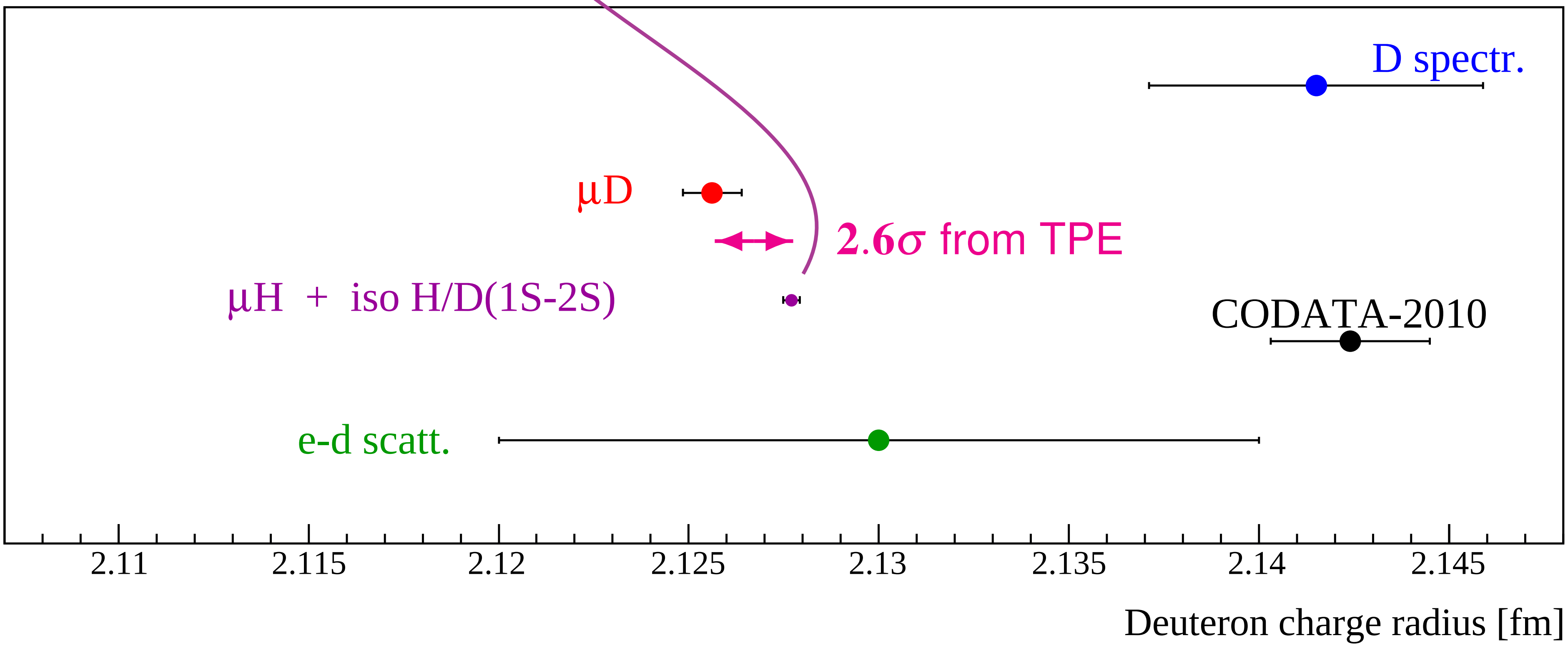


Conclusions μp and μd

Putting BSM scenarios aside,

- Muonic hydrogen gives:
  - Proton charge radius: r_p= 0.84087 (39) fm
  - Proton Zemach radius: R_Z = 1.082 (37) fm
  - Rydberg constant:

    $$R_\infty = 3.289\,841\,960\,249\,5\ (10)^{\text{radius}}\ (25)^{\text{QED}}\ \times 10^{15}\ \text{Hz/c}$$

  - Deuteron charge radius: r_d= 2.12771 (22) fm using H/D(1S-2S)
  - r_p is $\sim 7\sigma$ smaller than CODATA-2010

    4.0σ smaller than r_p(H spectrosopy)

- Muonic deuterium gives:
  - r_d is 7.5σ smaller than CODATA-2010 (99% correlated with r_p!)

    3.5σ smaller than r_d(D spectrosopy)

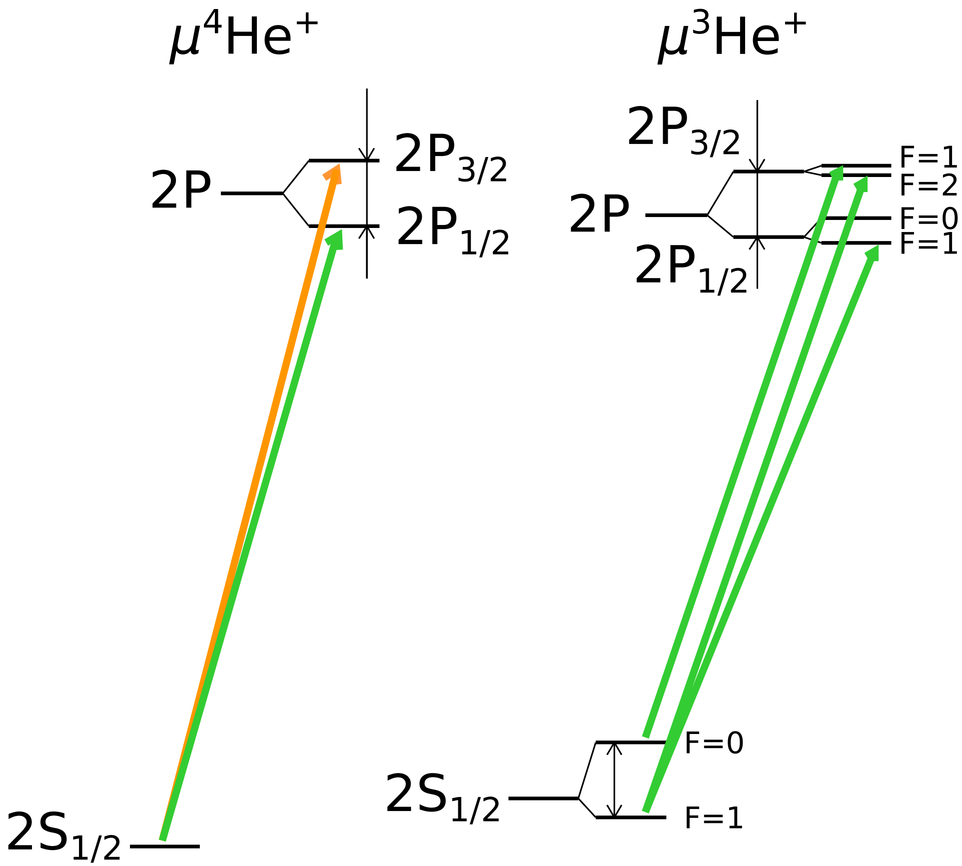
  - TPE contribution to Lamb shift: $\Delta E_{LS}^{TPE}(\text{exp})$ = 1.7638(68) meV

    2.6σ larger, but 3x more accurate than theory 1.7096(200) meV

  - TPE contribution to 2S-HFS: $\Delta E_{HFS}^{TPE}(\text{exp})$ = 0.2178(74) meV

    in good agreement with theor. estimate 0.2226(49) meV

Muonic helium ions



Lamb shift in muonic helium

- Goal: Measure ΔE(2S-2P) in $\mu\,^4$He, $\mu\,^3$He to ~ 50 ppm
- ⇒ alpha particle and helion charge radius to 3×10^{-4} (± 0.0005 fm),

  This is **10 times better** than from electron scattering.
- Solve discrepancy in ^{3}He - ^{4}He isotope shift.

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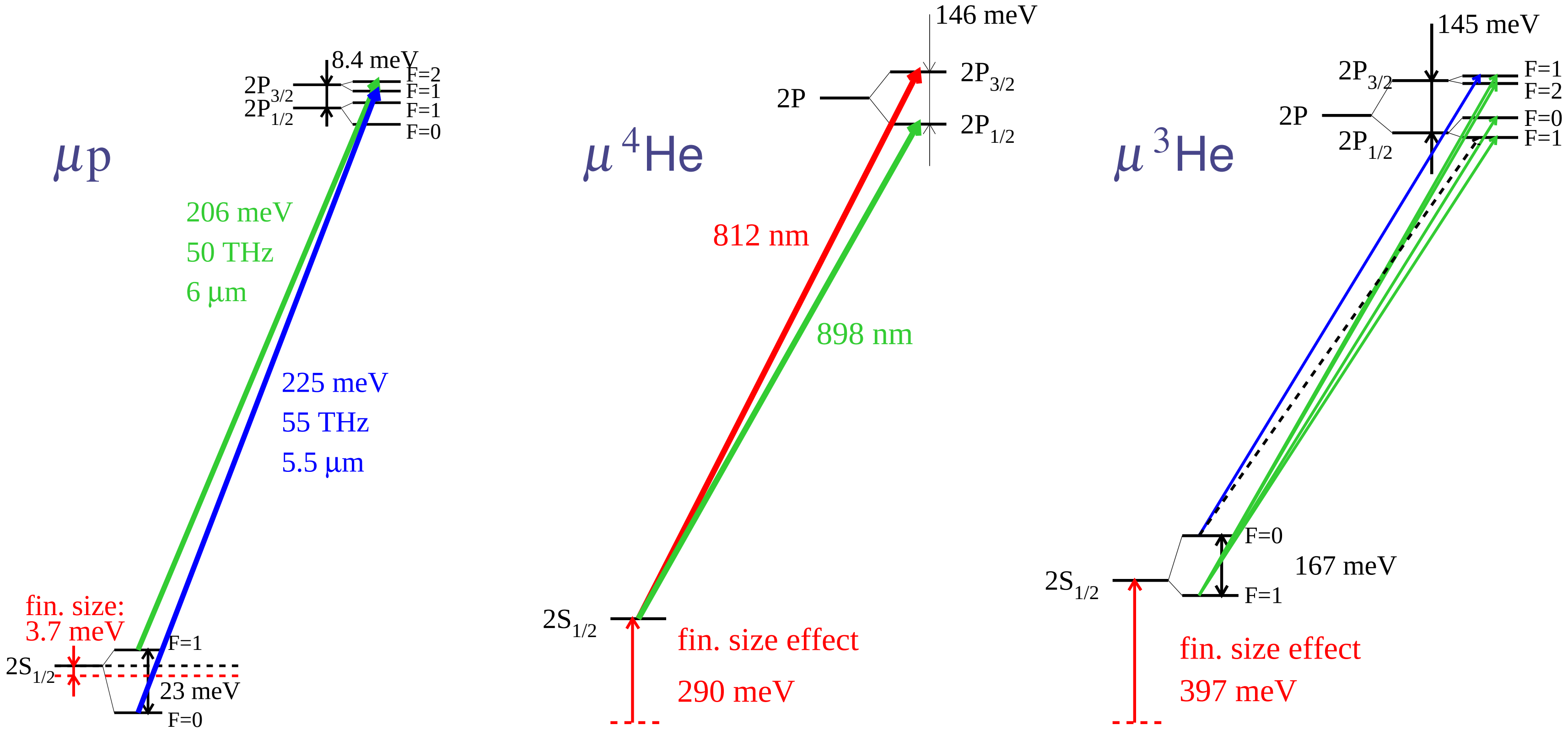
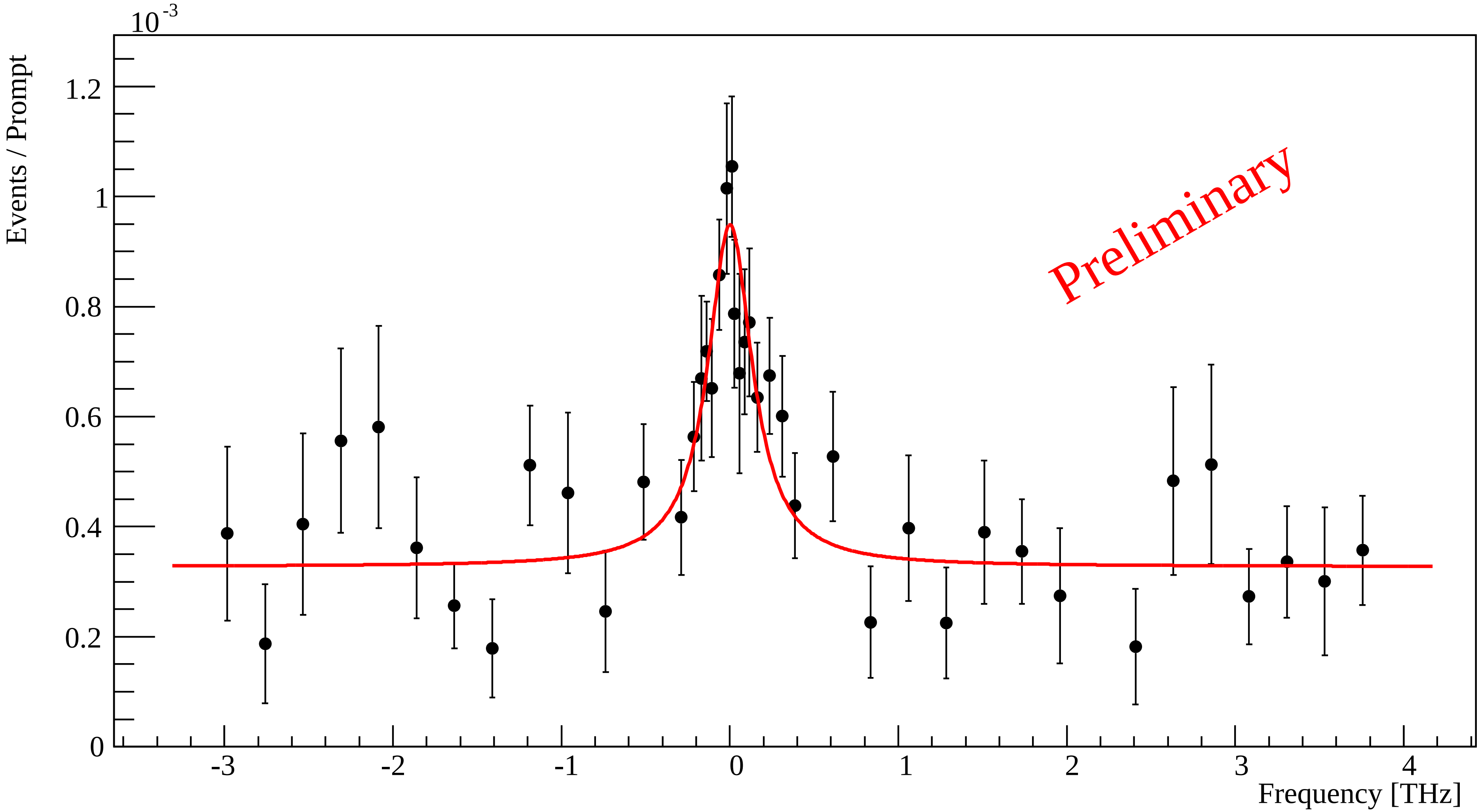


1st resonance in muonic He-4

$\mu^4\text{He}(2S_{1/2} \rightarrow 2P_{3/2})$ at ~ 813 nm wavelength



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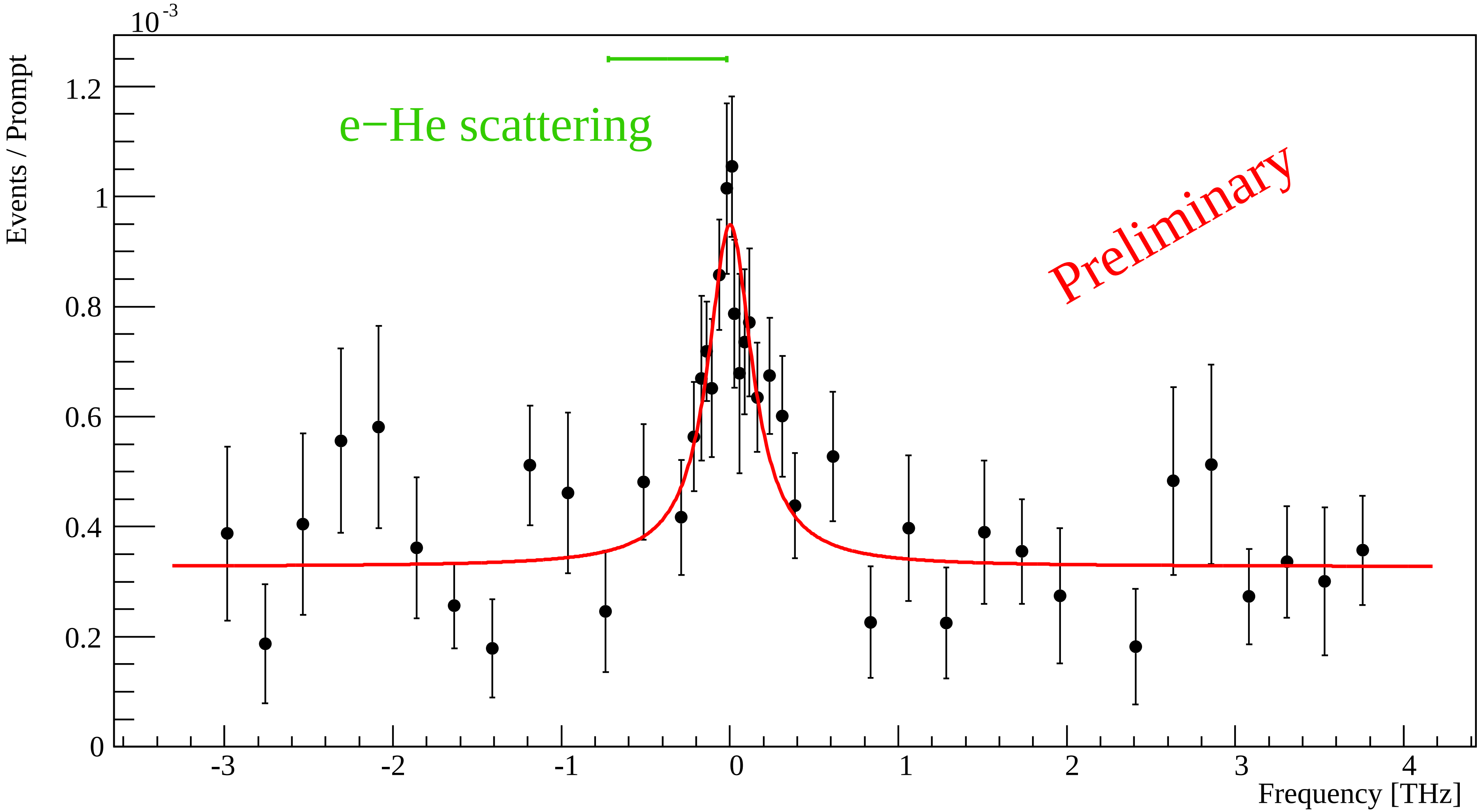

Sick, PRD 77, 040302(R) (2008) Borie, Ann. Phys. 327, 733 (2012)

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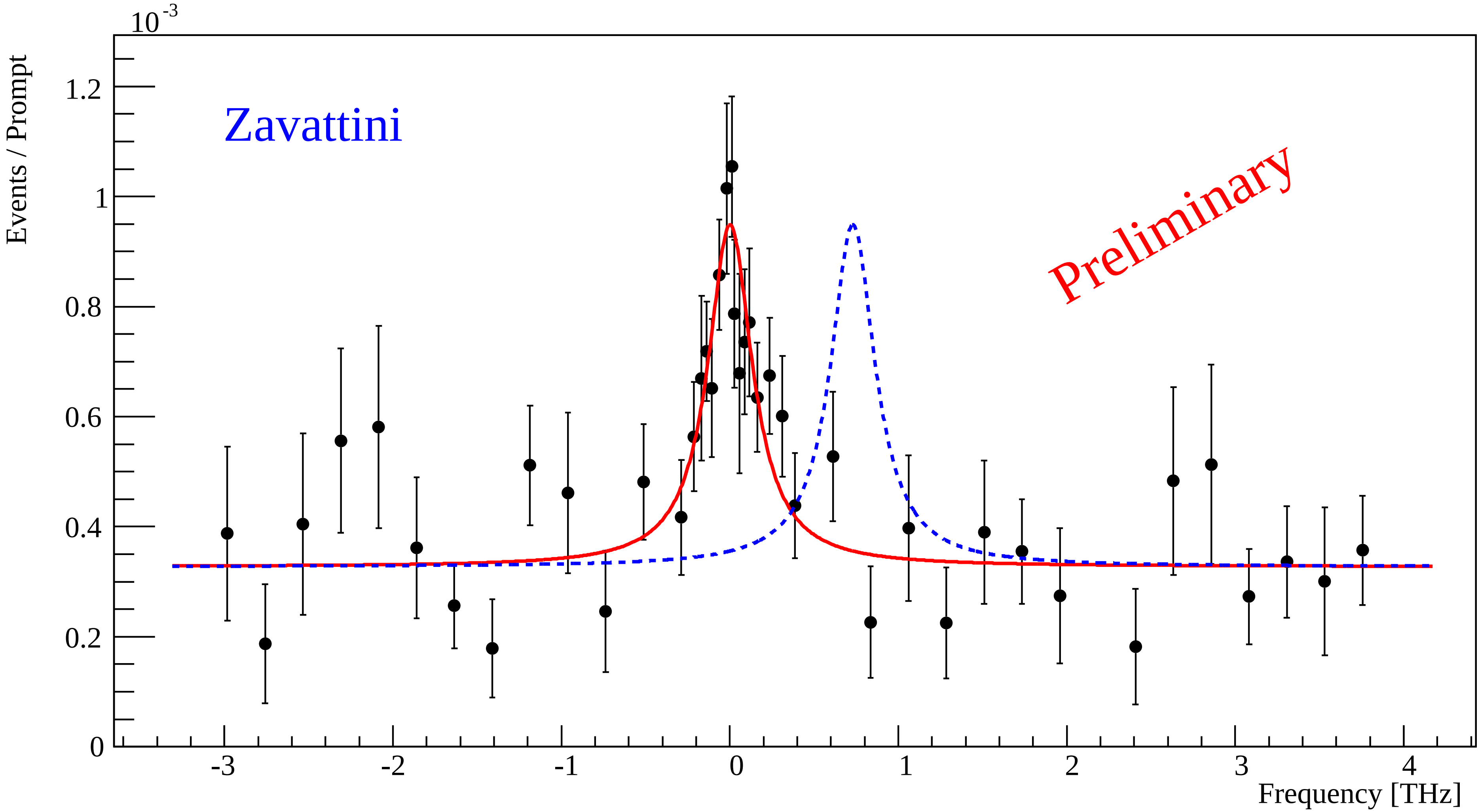

Carboni et al, Nucl. Phys. A273, 381 (1977)

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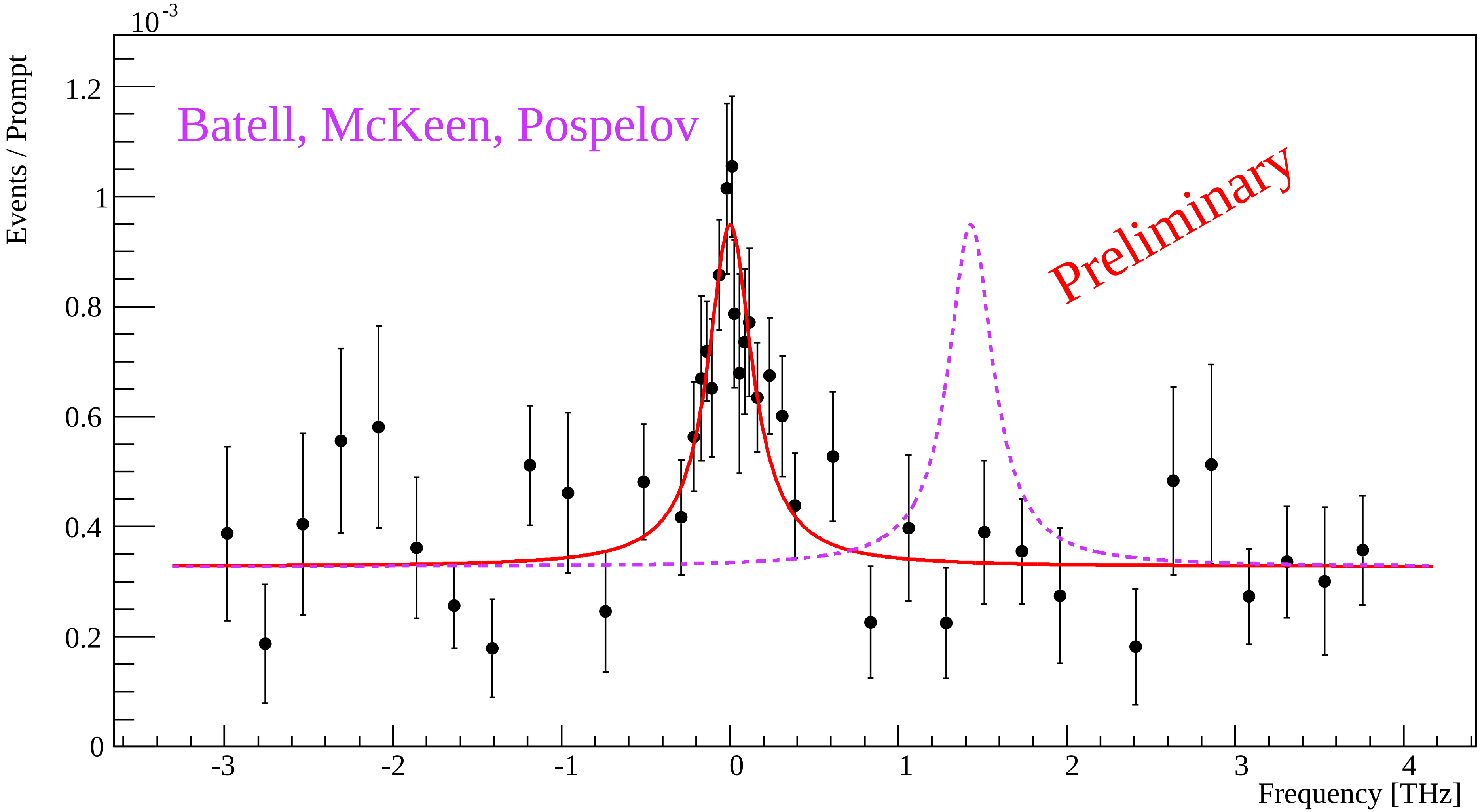

Batell, McKeen, Pospelov, PRL 107, 011803 (2011)

Muonic summary

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  - Proton charge radius: r_p= 0.84087 (39) fm
    7σ away from electronic average (CODATA: H, e-p scatt.)
  - Deuteron charge radius: $r_d = 2.12771\,(22)$ fm from μH + H/D(1S-2S)
- Muonic deuterium:
  - Deuteron charge radius: $r_d = 2.12562\,(13)_{\text{exp}}\,(77)_{\text{theo}}$ fm (PRELIMINARY!)
    consistent with muonic proton radius, but
    again 7σ away from CODATA: $2.14240\,(210)$ fm

RP *et al.*, submitted (2016)

- "Proton" Radius Puzzle is in fact "Z=1 Radius Puzzle"
- muonic helium-3 and -4 ions: No big discrepancy (PRELIMINARY)

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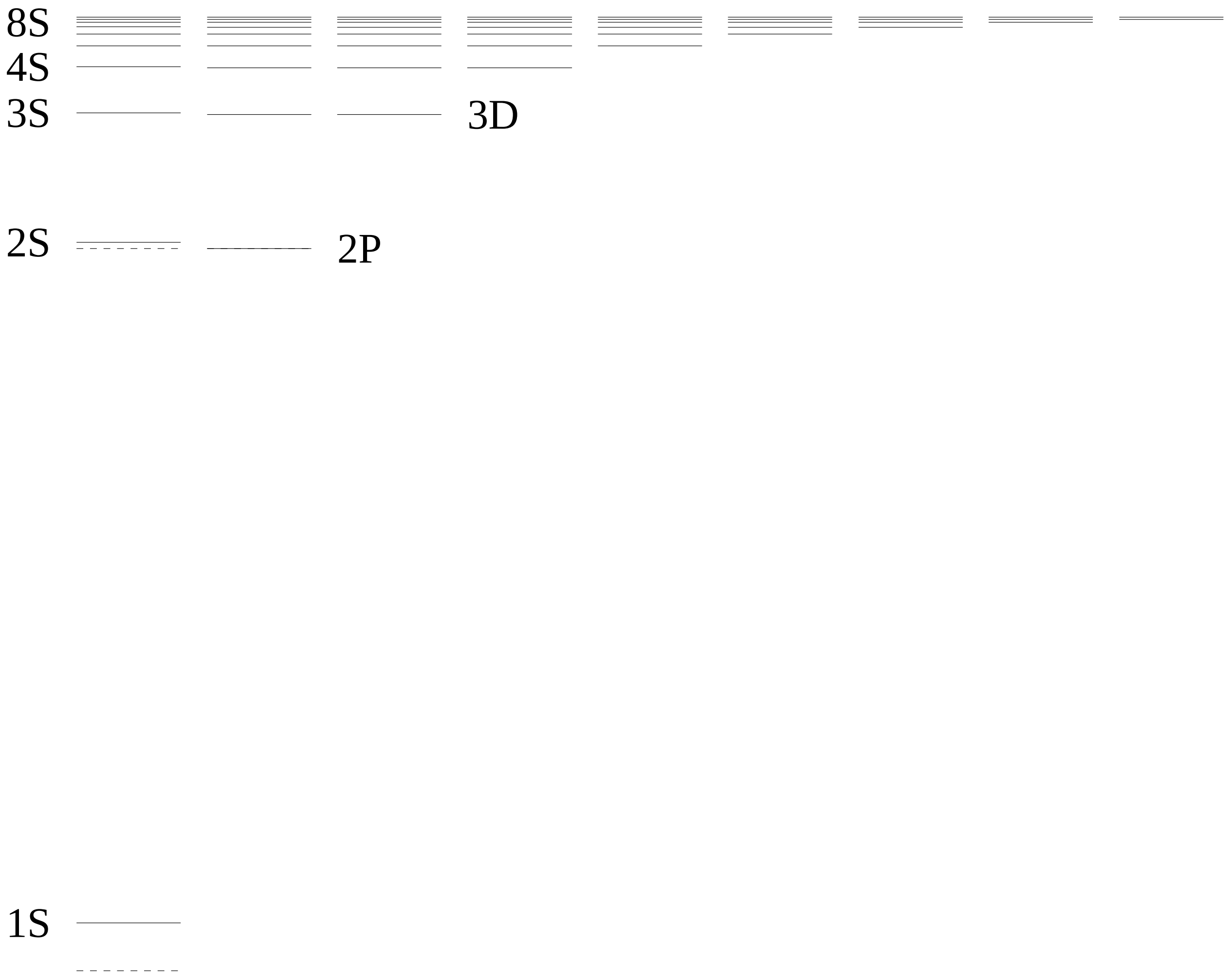
- muonic helium-3 and -4 ions: No big discrepancy (PRELIMINARY)
- Could **ALL** be solved if the **Rydberg constant** [and hence the (electronic) proton radius] was wrong.
  Plus $\sim 2.6\sigma$ change in deuteron polarizabililty.
  Plus: accept dispersion fits of e-p scattering
- Or: BSM physics, e.g. Tucker-Smith & Yavin (2011)

(Electronic) hydrogen.

Hydrogen spectroscopy

$$\text{Lamb shift}: \quad L_{1S}(r_p) = 8171.636(4) + 1.5645 \langle r_p^2 \rangle \text{ MHz}$$

$$L_{nS} \simeq \frac{L_{1S}}{n^3}$$



RP *et al.* arXiv 1607.03165

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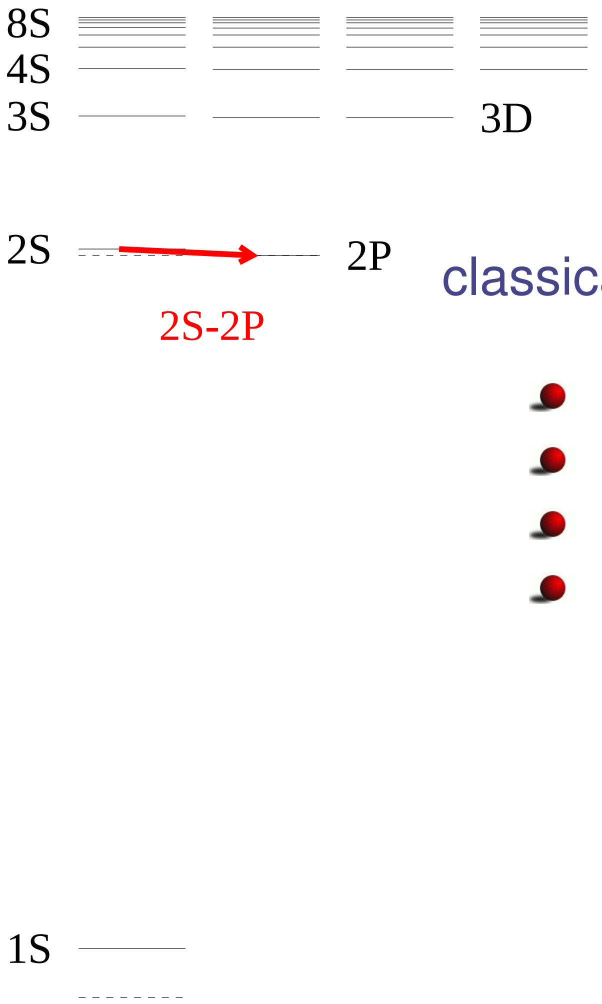
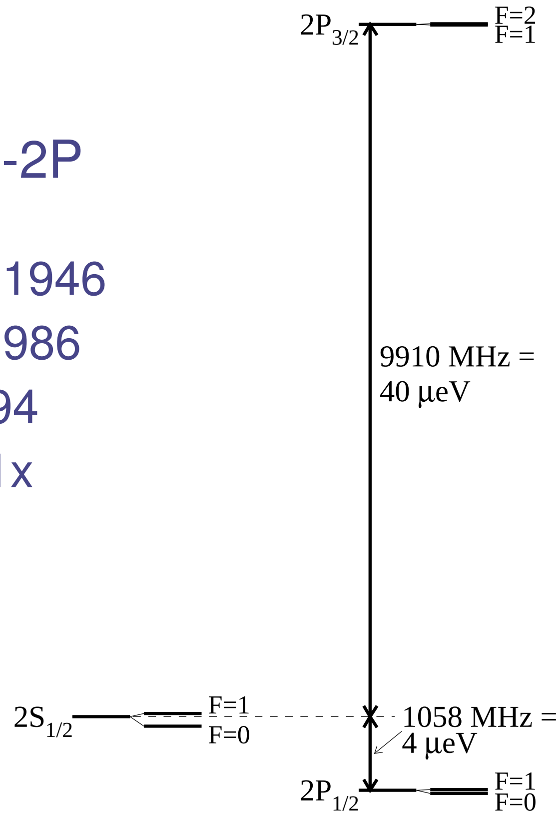


classical Lamb shift: 2S-2P

- Lamb, Retherford 1946
- Lundeen, Pipkin 1986
- Hagley, Pipkin 1994
- Hessels *et al.*, 201x



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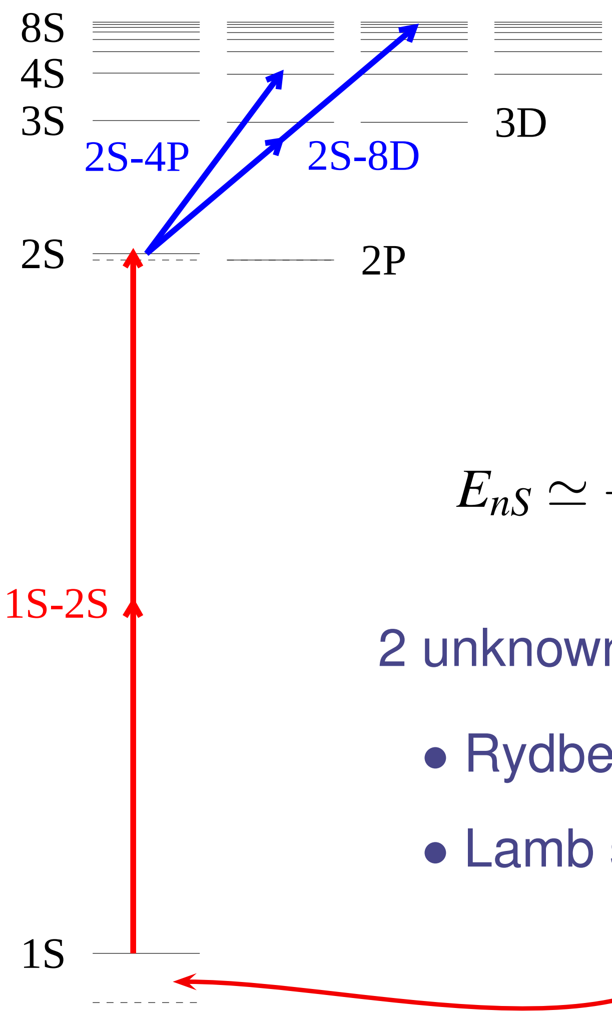


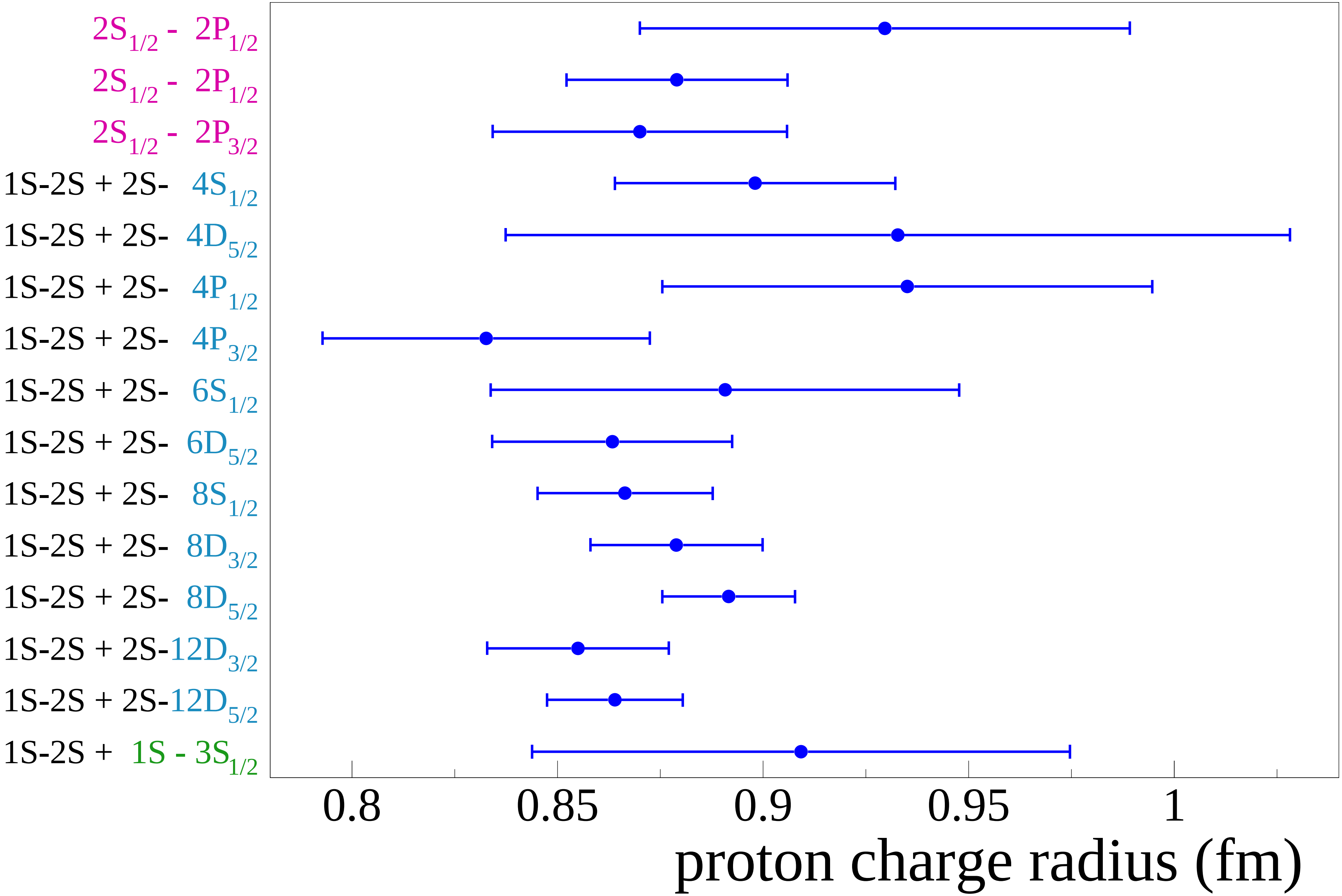
$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

2 unknowns ⇒ 2 transitions

- Rydberg constant R_∞
- Lamb shift $L_{1S} \leftarrow r_p$

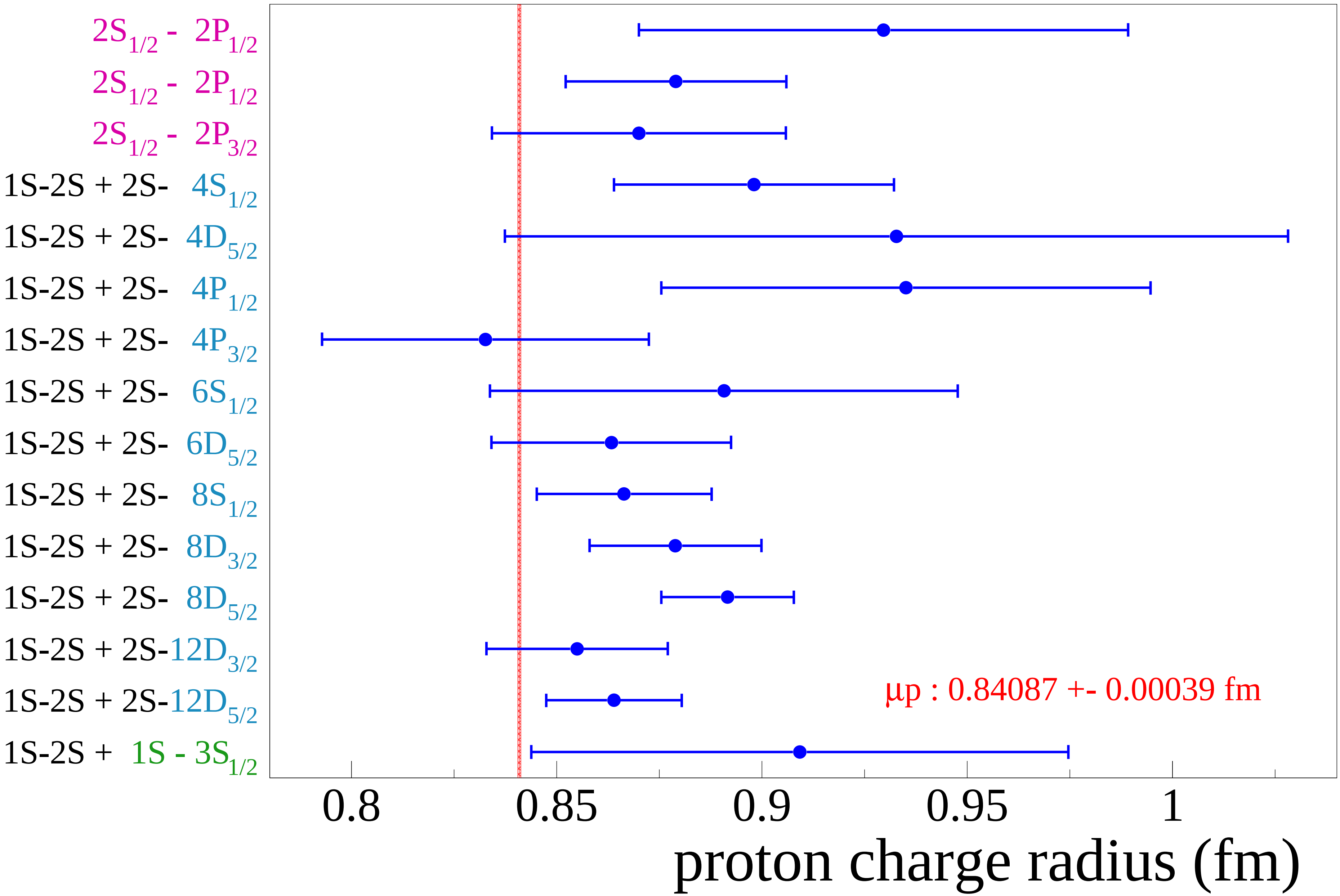
RP *et al.* arXiv 1607.03165

Hydrogen spectroscopy



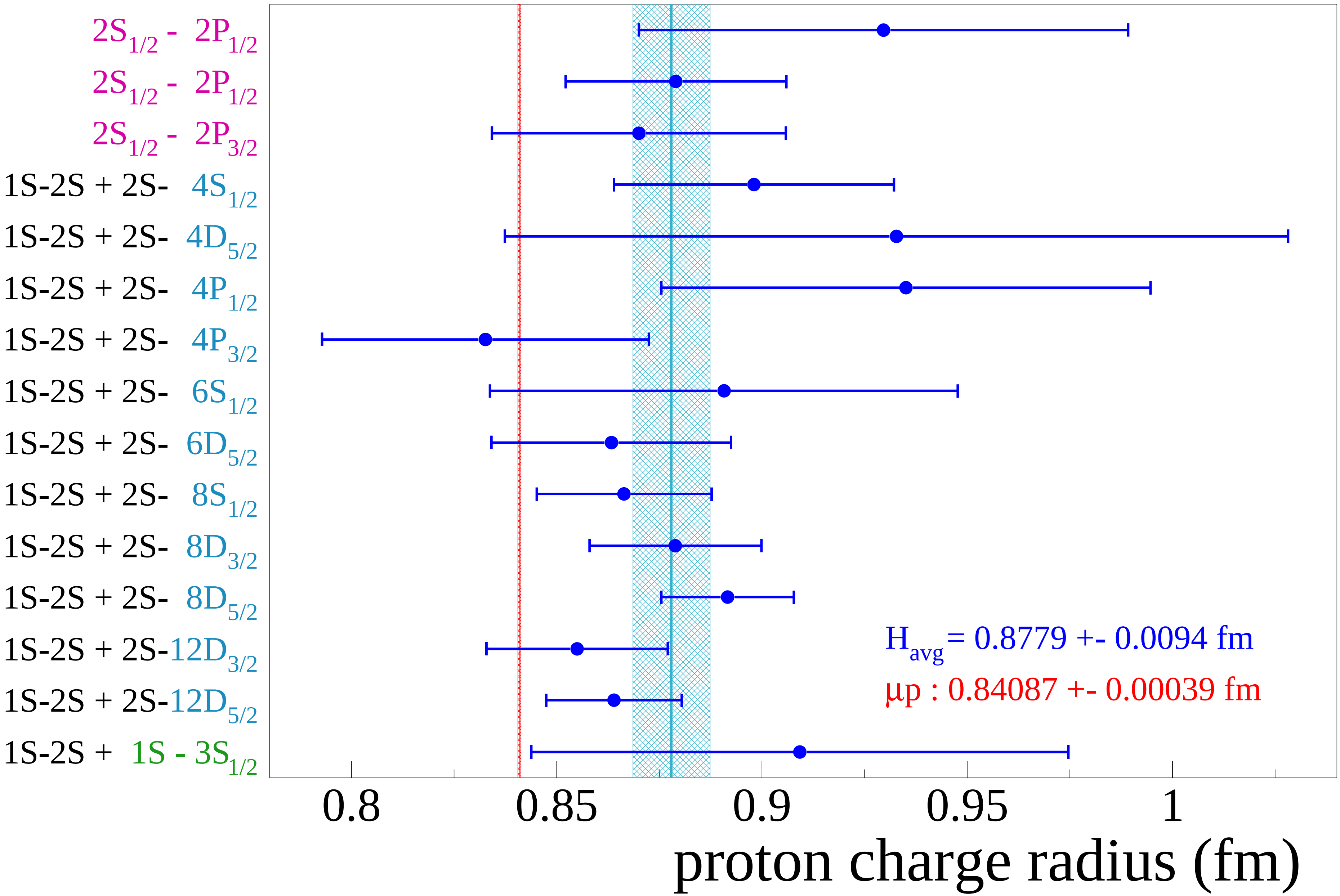
RP *et al.* arXiv 1607.03165

Hydrogen spectroscopy



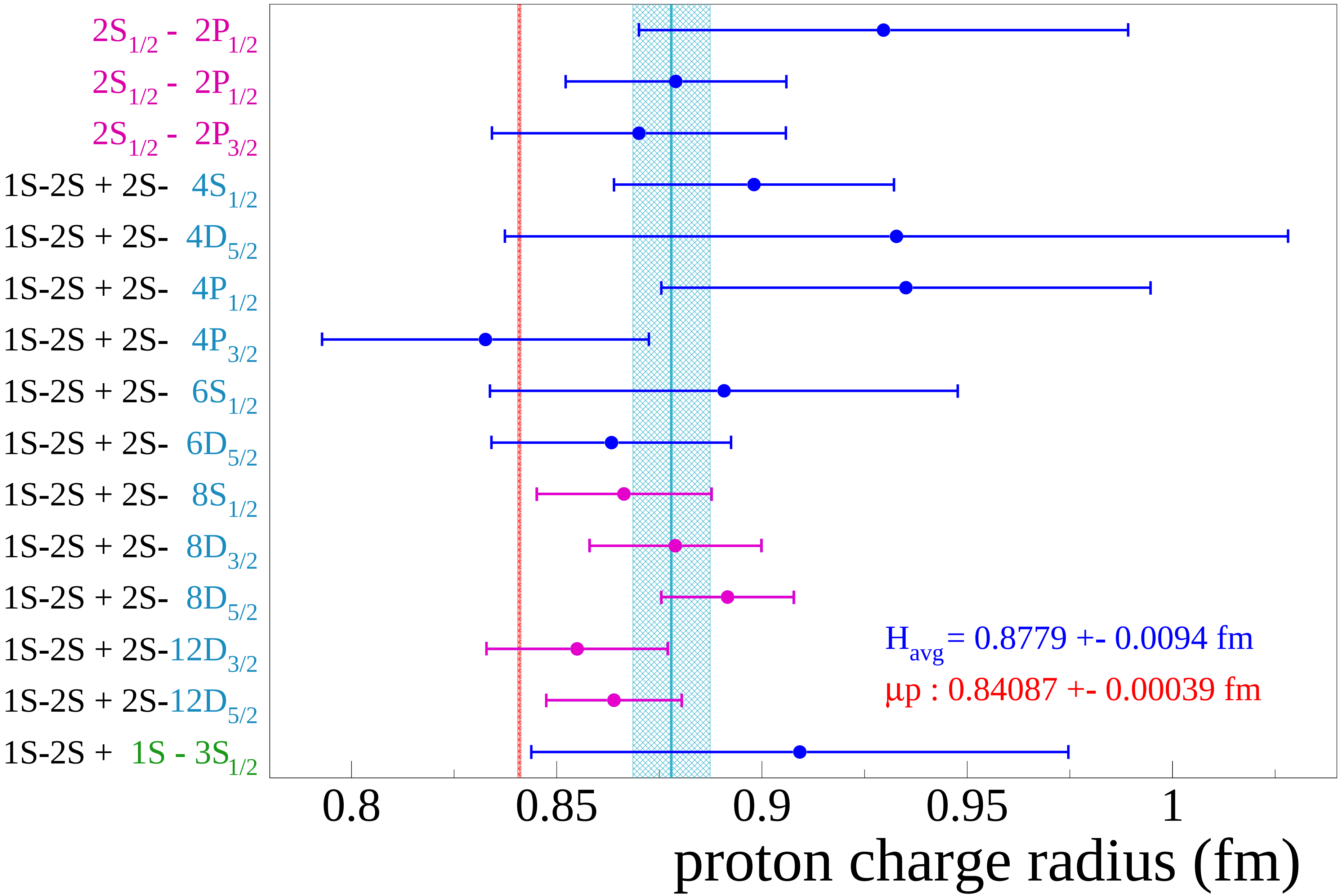
RP *et al.* arXiv 1607.03165

Hydrogen spectroscopy



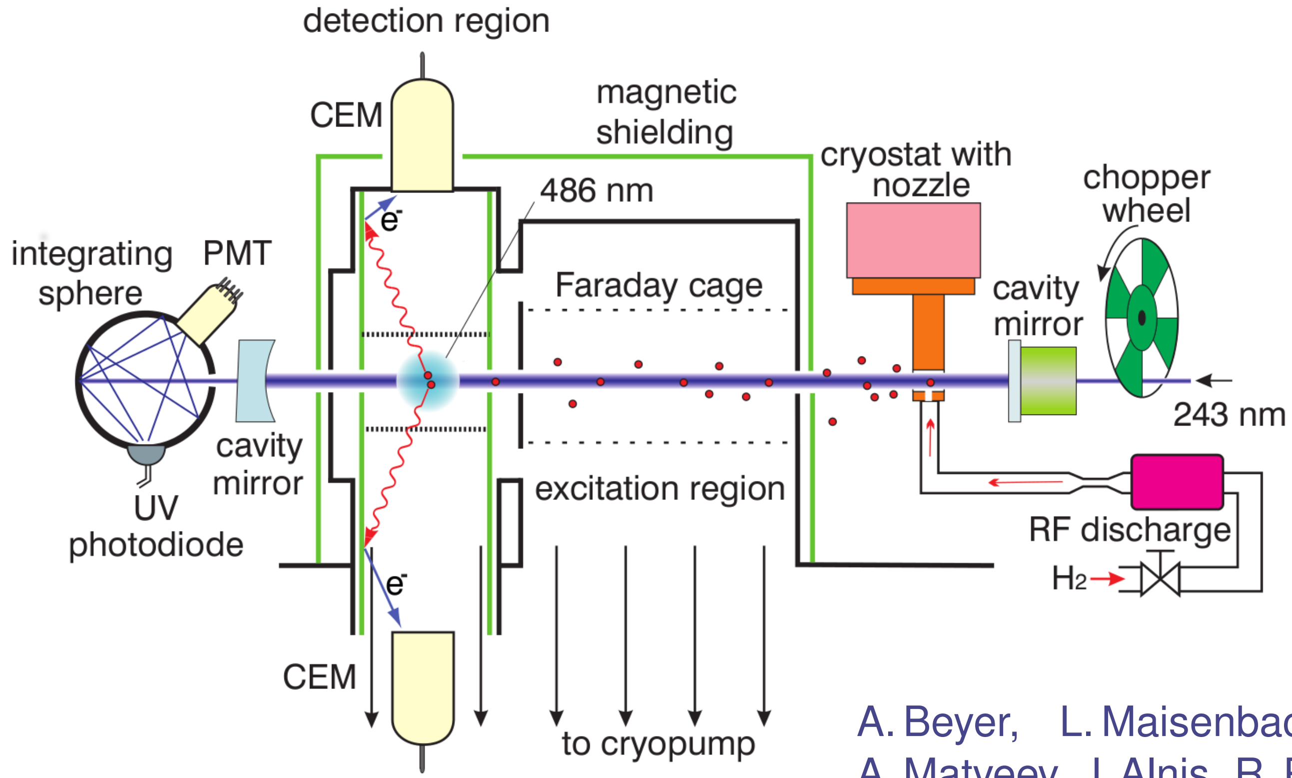
RP *et al.* arXiv 1607.03165

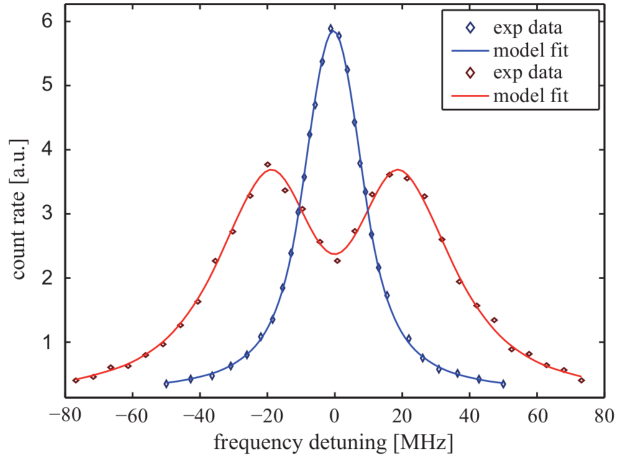
Hydrogen spectroscopy



RP *et al.* arXiv 1607.03165

Rydberg constant from hydrogen





2S – 4P resonance at $88 \pm 0.5\,^\circ$ and $90 \pm 0.08\,^\circ$

A. Beyer, L. Maisenbacher, K. Khabarova, C.G. Parthey, A. Matveev, J. Alnis, R. Pohl, N. Kolachevsky, Th. Udem and T.W. Hänsch

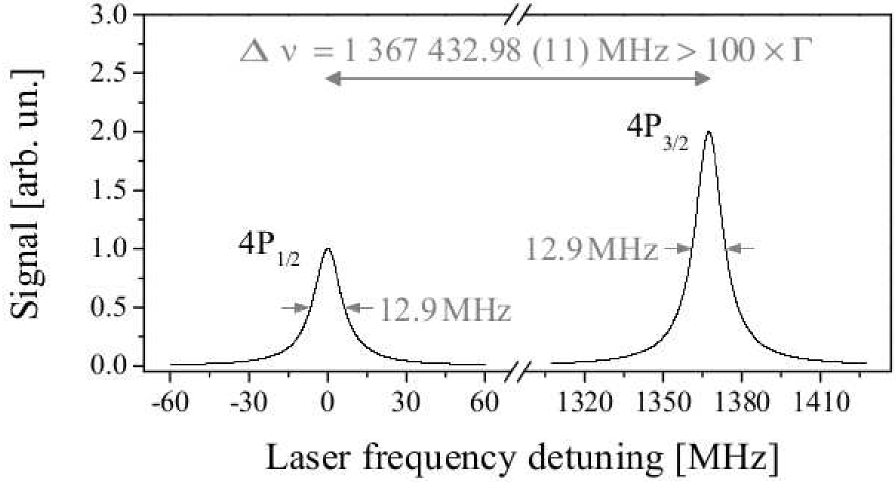
- Apparatus used for H/D(1S-2S)

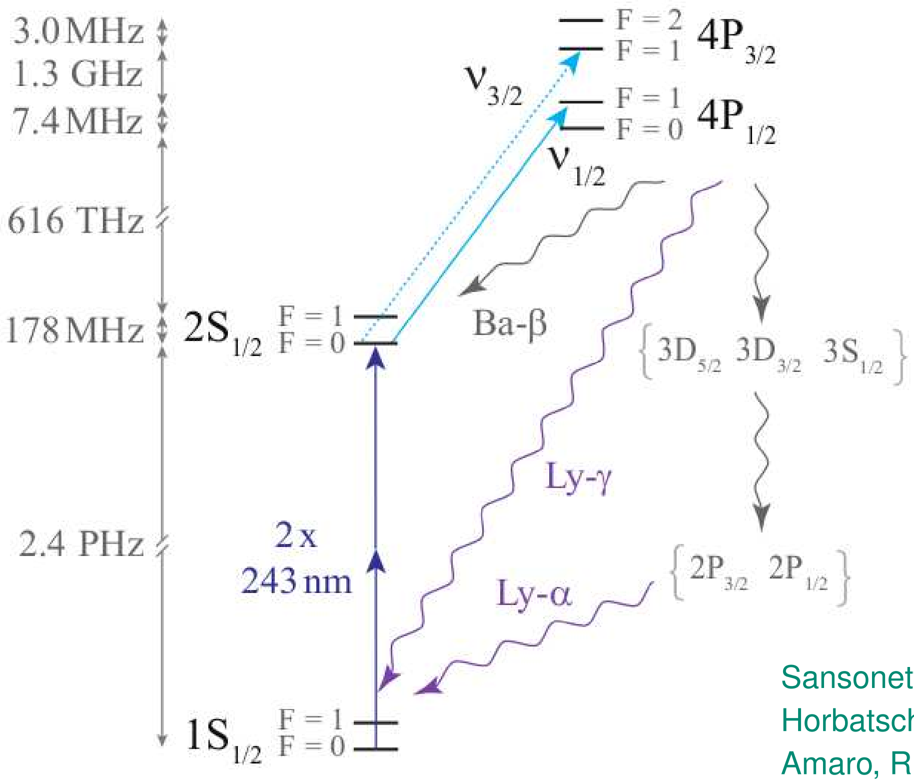
C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)
C.G. Parthey, RP *et al.*, PRL **107**, 203001 (2011)

- 486 nm at 90° + Retroreflector $\Rightarrow$ Doppler-free 2S-4P excitation
- 1st oder Doppler vs. ac-Stark shift
- ~ 2.5 kHz accuracy (vs. 15 kHz Yale, 1995)
- **cryogenic** H beam, **optical** excitation to 2S

A. Beyer, RP *et al.*, Ann. d. Phys. **525**, 671 (2013)

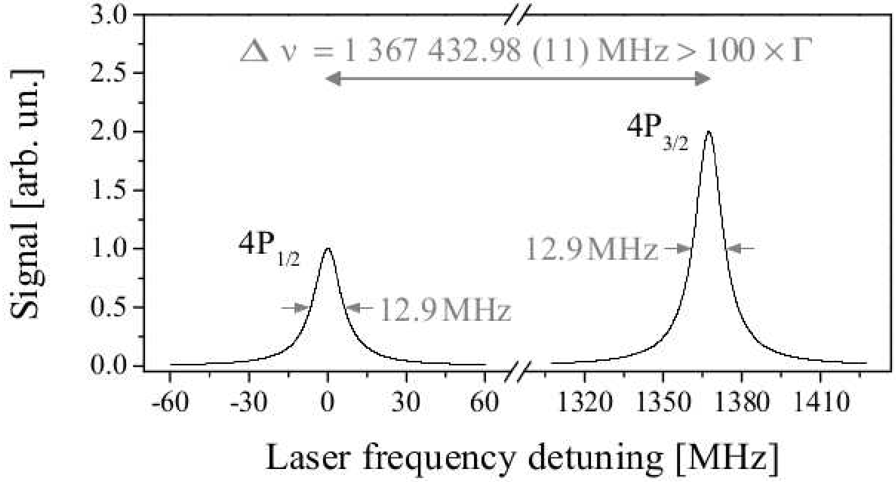
Quantum interference shifts

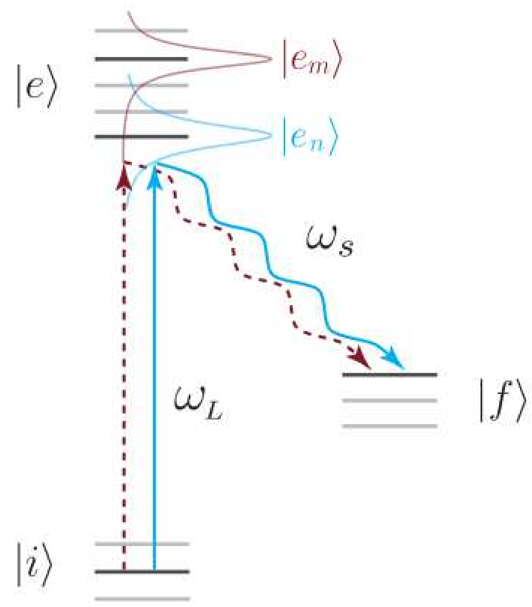


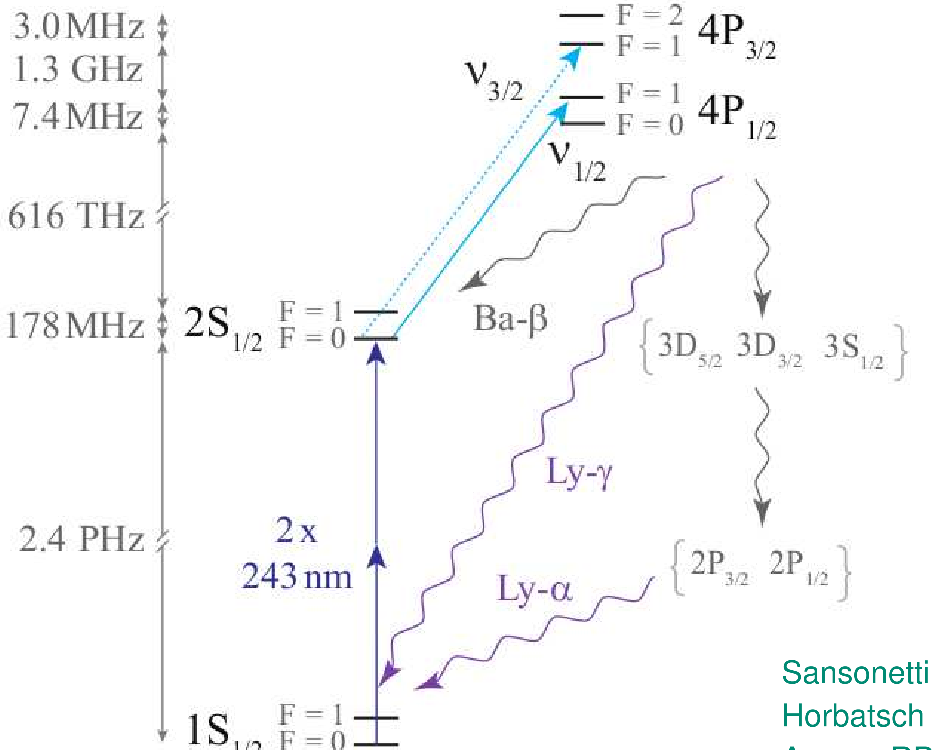


Sansonetti *et al.*, PRL 107, 023001 (2011); Brown *et al.*, PRA 87, 032504 (2013)
Horbatsch & Hessels, PRA 82, 052519 (2010); PRA 84, 032508 (2011), etc.
Amaro, RP *et al.*, PRA 92, 022514 (2015); PRA 92, 062506 (2015)

Quantum interference shifts







$$P(\omega) \propto \left| \frac{(\vec{d}_1 \cdot \vec{E}_0)\vec{d}_1}{\omega_1 - \omega_L + i\gamma_1/2} + \frac{(\vec{d}_2 \cdot \vec{E}_0)\vec{d}_2 e^{i\Delta\phi}}{\omega_2 - \omega_L + i\gamma_2/2} \right|^2$$

= Lorentzian(1) + Lorentzian(2) +

cross-term (QI)

Sansonetti *et al.*, PRL 107, 023001 (2011); Brown *et al.*, PRA 87, 032504 (2013)
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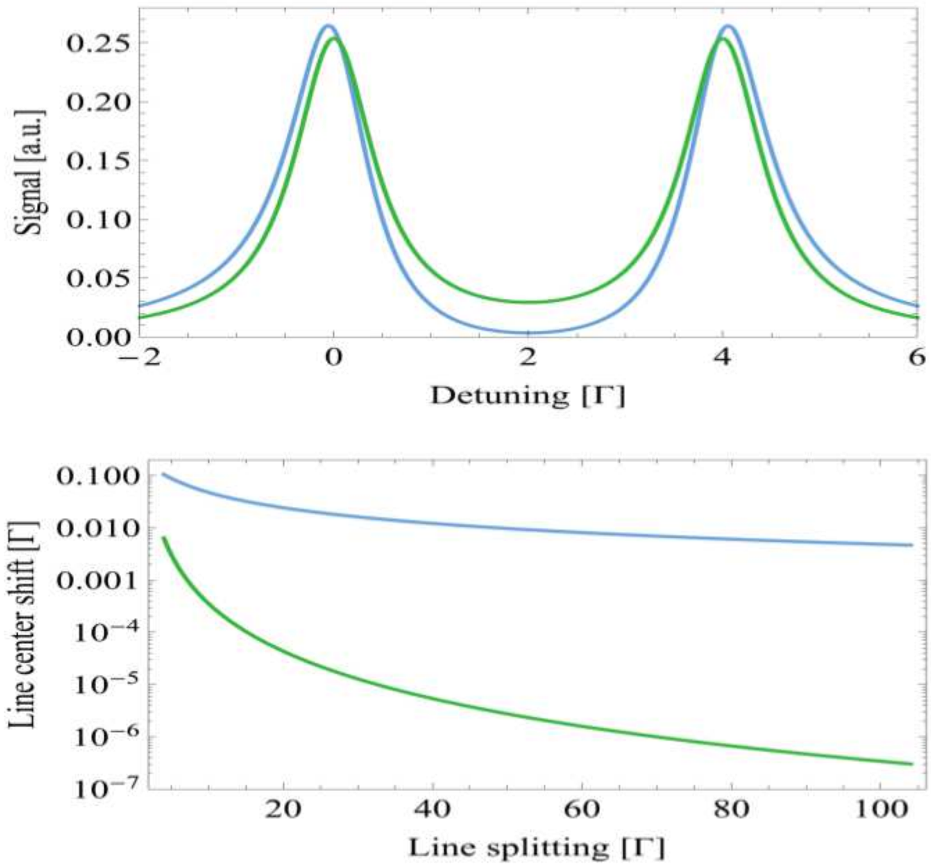

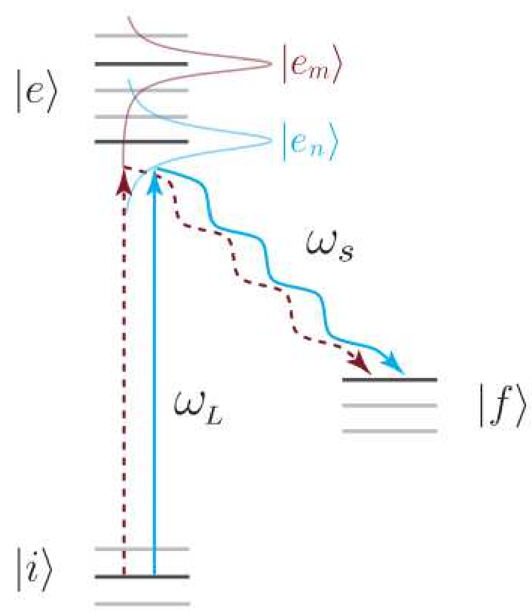

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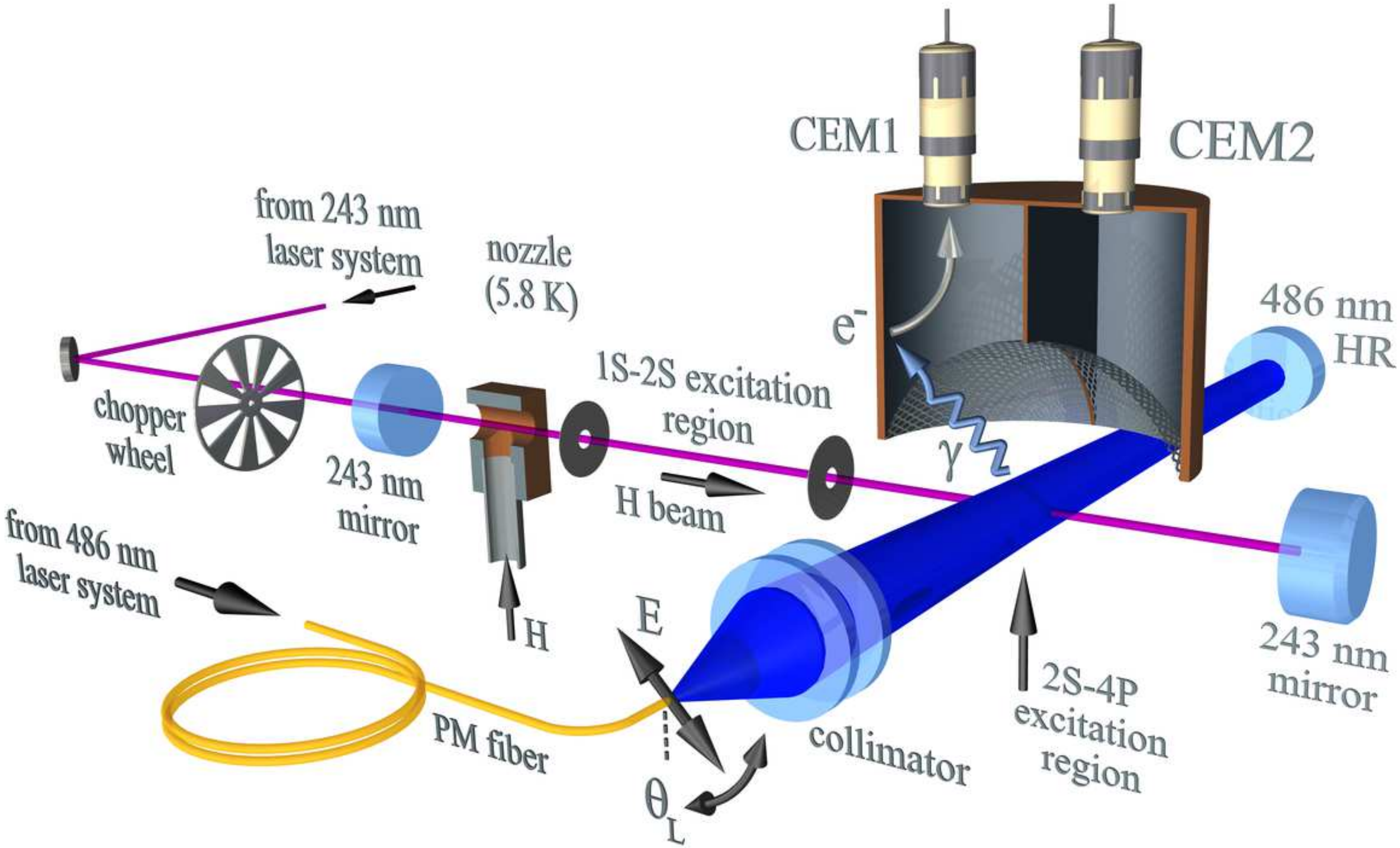
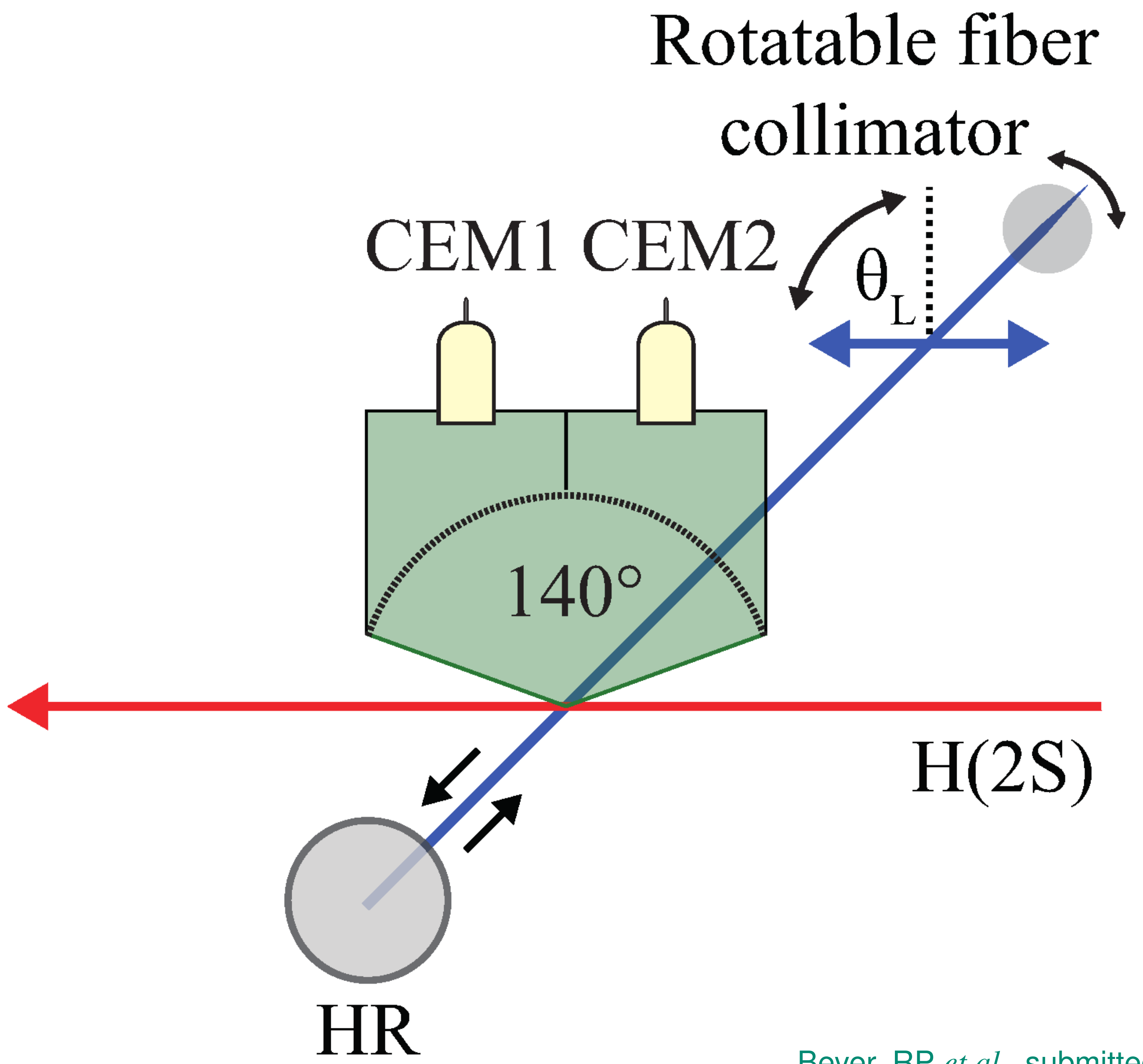
Quantum interference shifts

2S-4P setup



Beyer, RP *et al.*, submitted (2016)

Quantum interference shifts



Beyer, RP *et al.*, submitted (2016)

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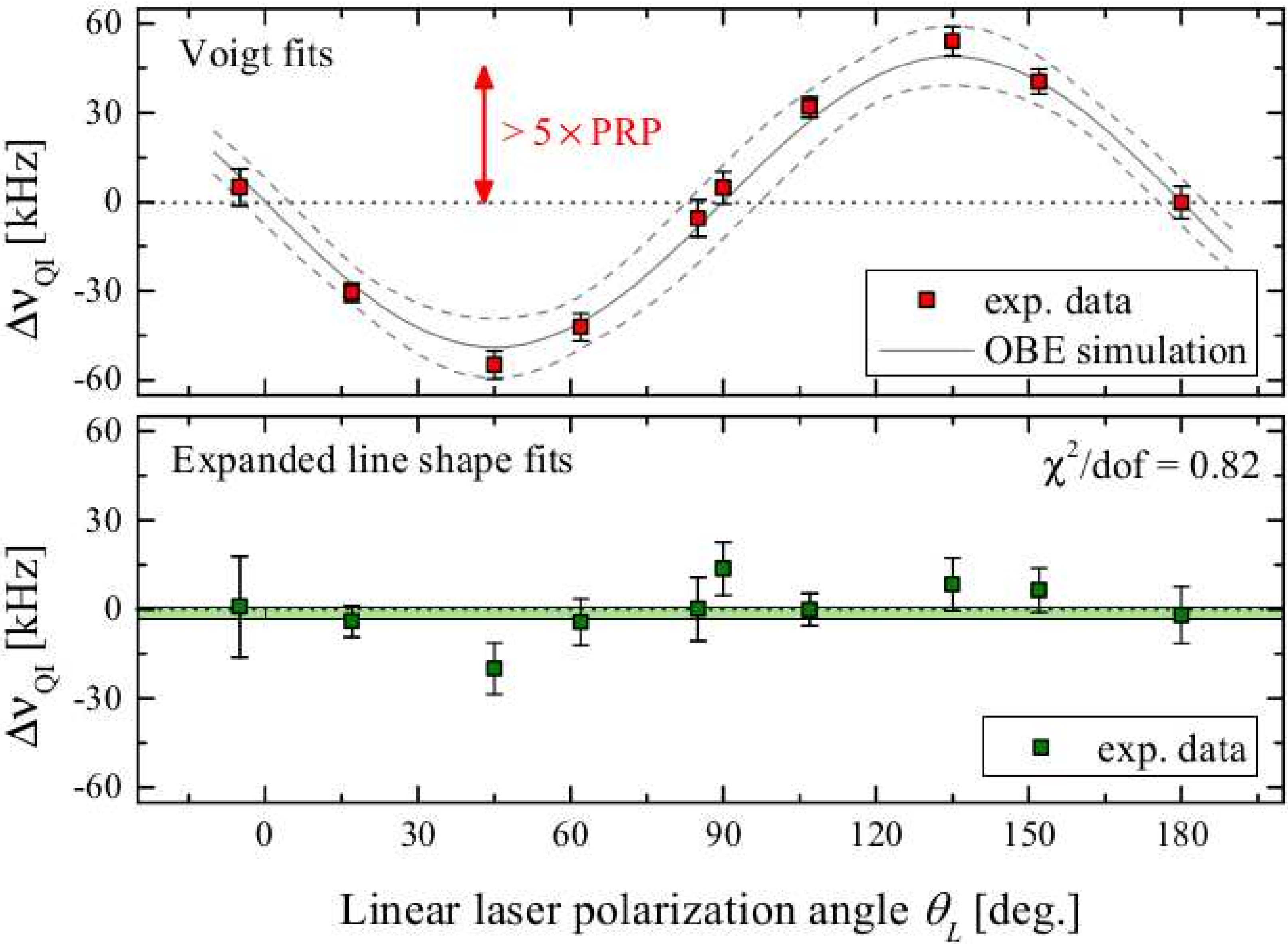
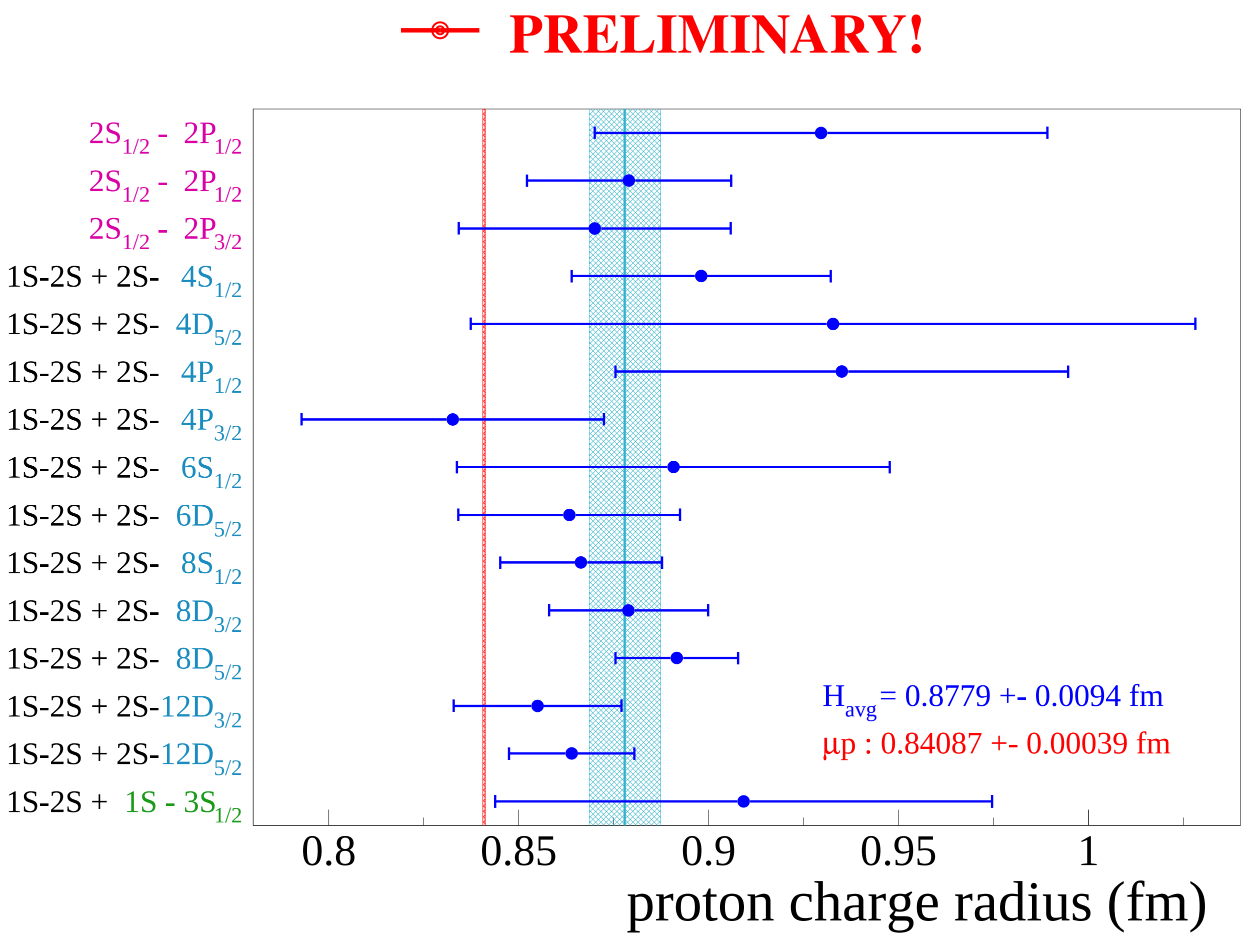


Beyer, RP *et al.*, submitted (2016)

New hydrogen 2S→4P at MPQ!



$2S \to 4P_{1/2}$ and $4P_{3/2}$

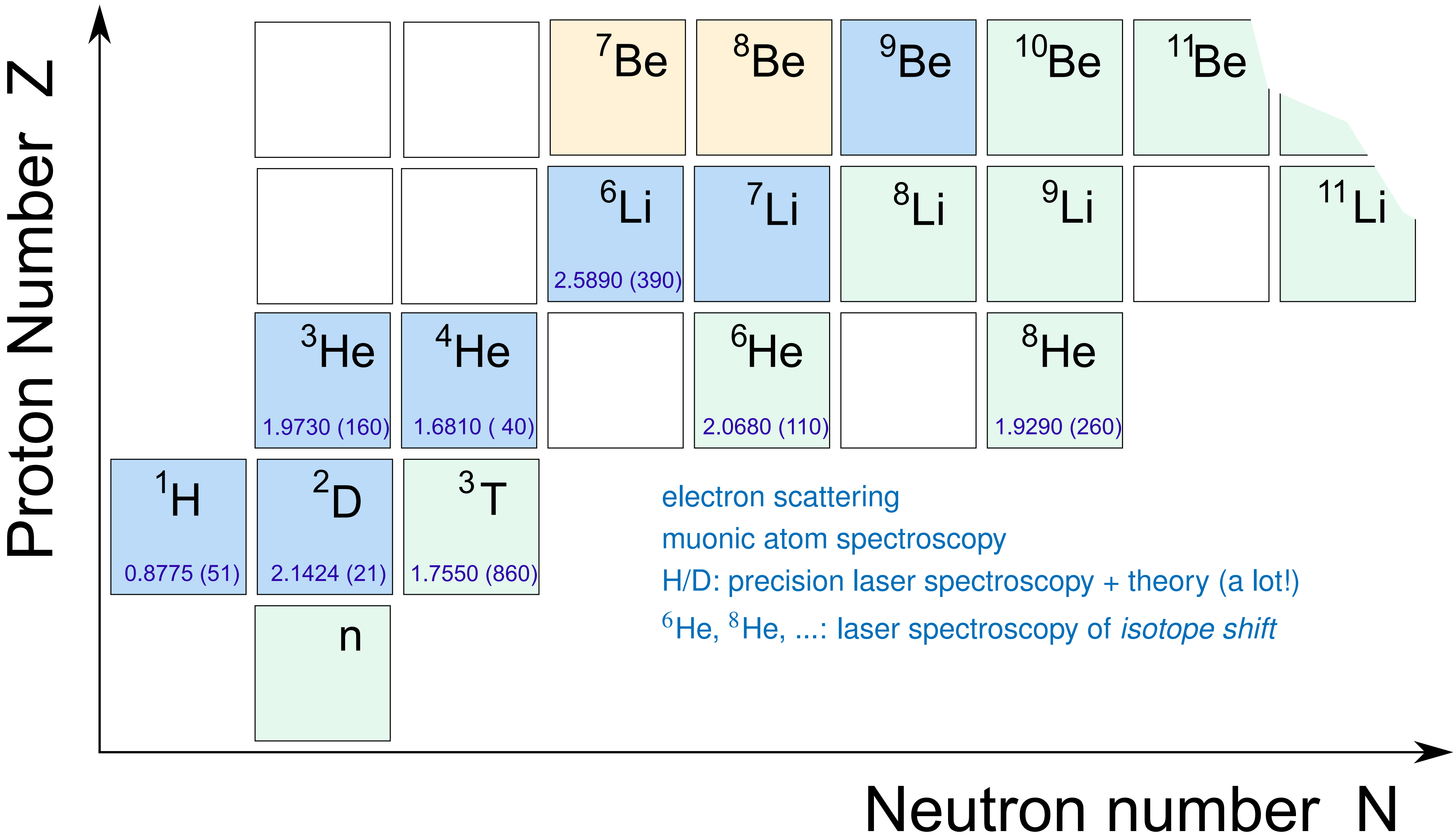
cold H(2S) beam

optically excited $(1S \to 2S)$

$\Delta\nu \sim 2\,\text{kHz} \quad \equiv \Gamma/10'000$!!!

Beyer, Maisenbacher, Matveev, RP, Khabarova, Grinin, Lamour, Yost, Hänsch, Kolachevsky, Udem, submitted (2016)

The nuclear chart



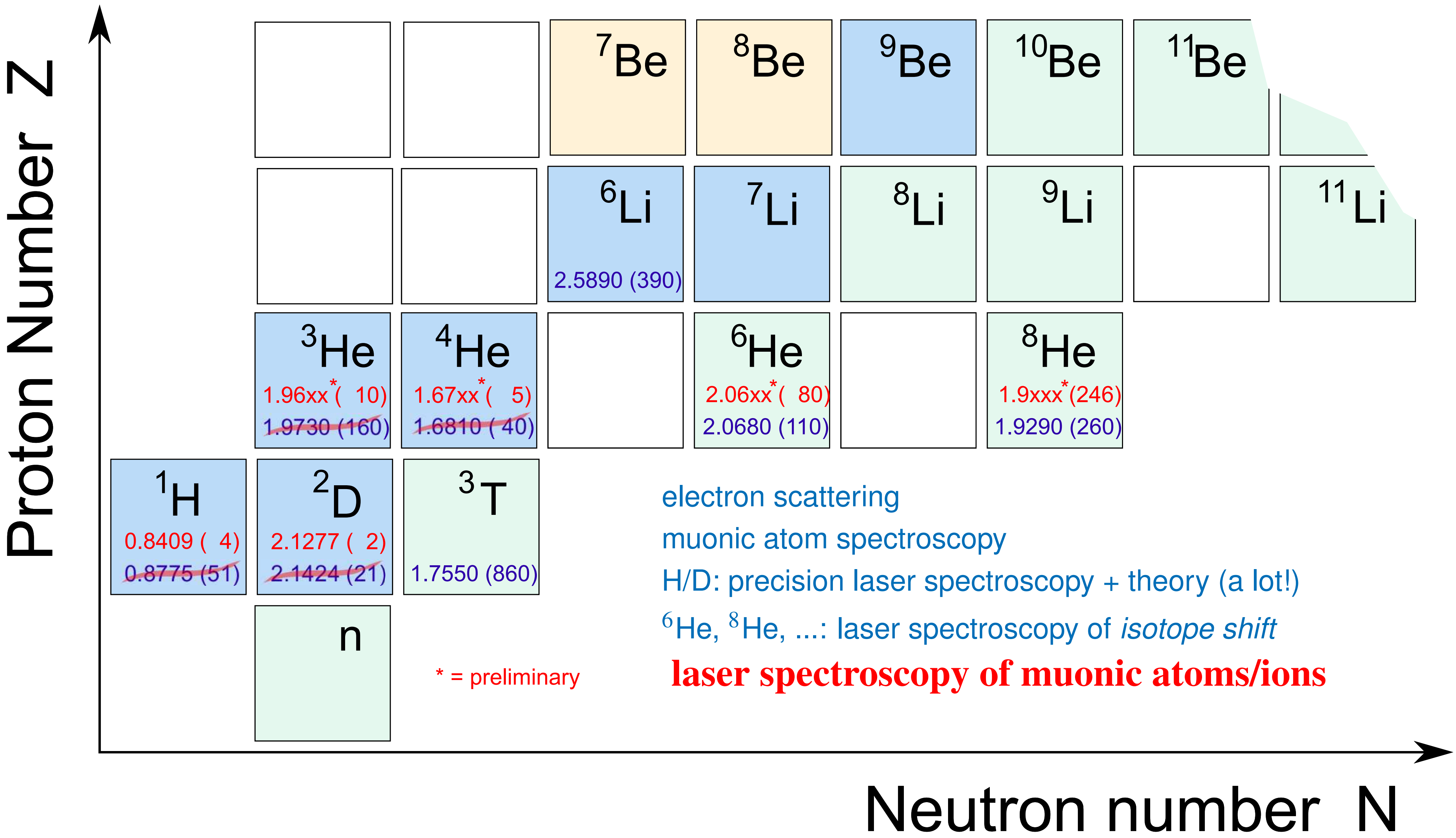
electron scattering

muonic atom spectroscopy

H/D: precision laser spectroscopy + theory (a lot!)

^{6}He, ^{8}He, ...: laser spectroscopy of *isotope shift*

The nuclear chart - new charge radii



Summary

- Results from muonic hydrogen:
  - Proton charge radius: r_p= 0.84087 (39) fm
  - Proton Zemach radius: R_Z = 1.082 (37) fm
  - Rydberg constant: $R_\infty = 3.289\,841\,960\,249\,5\ (10)^{r_p}\ (25)^{QED}\ \times 10^{15}$ Hz/c
  - Deuteron charge radius: r_d = 2.12771 (22) fm from μH + H/D(1S-2S)
  - The "Proton radius puzzle"
- Muonic deuterium:
  - (r_d = 2.12562 (78) fm from μD)
  - TPE in Lamb shift: ΔE = 1.7638(68) meV, 2.6σ larger, 3x more accurate
  - TPE in 2S-HFS: ΔE = 0.2178(74) meV in good agreement with theory
- muonic helium-3 and -4: charge radius 10x more precise. No big discrepancy
- H(2S-4P) gives revised Rydberg $\Rightarrow$ small r_p PRELIMINARY

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- New projects:
  - 1S-HFS in muonic hydrogen / ^{3}He $\Leftarrow$ PSI, J-PARC, RIKEN-RAL, ...
  - LS in muonic Li, Be, B, T, ...; muonic high-Z, ...
  - 1S-2S and 2S-$n\ell$ in Hydrogen/Deuterium/Tritium, He^+
  - Positronium $\equiv e^+e^-$, Muonium $\equiv \mu^+e^-$
  - Electron scattering: H at lower Q^2, D, He
  - Muon scattering: MUSE @ PSI

CREMA in 2009...

Proton Size Investigators thank you for your attention

... and 2014